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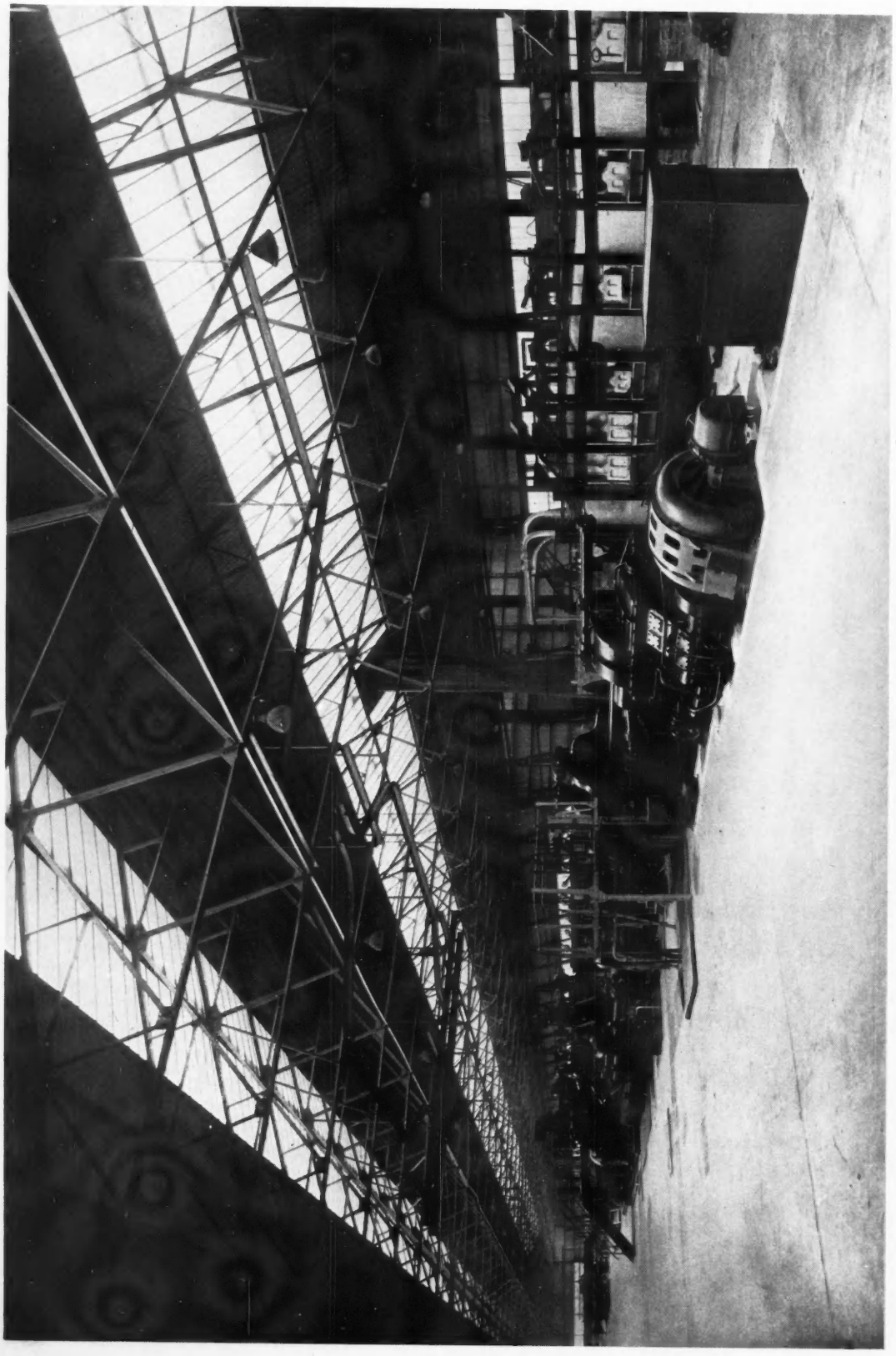


GENERAL VIEW OF MAIN ROLLING MILL BAY AT JARROW TUBE WORKS.
The equipment installed by the G.E.C. at this works includes motors for rolling mill, auxiliary drives, switchgear, cables, distribution gear, a continuous bright annealing furnace, lighting fittings and lamps and accessory gear of many kinds.

G.E.C. Journal

VOL. IX. NOVEMBER, 1938. No. 4.

The Economics of Very High Power Transmission over Long Distances.

By REINHOLD RÜDENBERG

G.E.C. Research Laboratories, Wembley, England.

The equipment installed by the G.E.C. at this works includes motors for rolling mill, auxiliary drives, switchgear, cables, distribution gear, a continuous bright annealing furnace, lighting fittings and lamps and accessory gear of many kinds.

There are strong reasons why the steam power stations of the future, with outputs of the order of 500,000 kW and more, should be erected in the neighbourhood of coal mines and preferably near the coast. Transmission of such quantities of power electrically becomes extremely economical when voltages of from 200 kV to 300 kV are employed. Under these conditions the cost of transmission over a distance of 160 miles is about 0·02—0·03 pence per kWh, which is only 10%—15% of the cost of generation, and much cheaper than hauling the equivalent amount of coal the same distance by rail.

In general, the cost of transmission drops steeply and continuously as the voltage rises, provided always that a load of sufficient magnitude is available. The special knowledge in regard to the construction and operation of long transmission systems acquired during the last decade now makes it possible for large blocks of electrical power of any desired amount to be transmitted very economically over long distances.

INTRODUCTION.

DURING the last century and the early decades of the present one, industry, for the most part, settled in the immediate neighbourhood of the natural sources of power, either coal or water. But the development of transport facilities and the transmission of electrical energy at high voltages have begun to change all this, and to-day—in Great Britain, for instance, with the 132 kV Grid, shown diagrammatically in fig. 1—it is possible to supply any part of the country with all the electrical power it requires for industrial and domestic purposes.

The question now arises whether to build new power stations near the centres of consumption or near the coal mines, as represented pictorially by figs. 2a and 2b. This, of course, is a very old problem, but the development of modern high voltage transmission lines and the increasing efficiency of large steam turbines have introduced some new factors of predominating importance, which must be taken into account.

The economics of the long distance transmission of large quantities of power electrically by means of overhead lines will therefore be considered on the basis of all the knowledge accumulated in this field during the last ten years. The investigation will deal firstly with some important questions relating to power stations and conclude with a comparison of the relative cost of conveying energy electrically and mechanically. So as to have a definite basis upon which to work, it will be assumed that an output of 500 MW, *i.e.*, 500,000 kW, is to be transmitted over a distance of 160 miles, which, as can be seen from fig. 1, is the actual distance of several coalfields from a number of industrial areas in Great Britain.

Both in Europe and America practice as regards the erection and operation of long transmission lines is well established, nevertheless the factors which determine the economy of the system as a whole are to a large extent variable, depending, as they do, on a great number of external conditions. Therefore, in order to arrive at a conclusion which can be easily surveyed, the procedure adopted will be either to consider every value over a definite range or to take averages deduced from actual operating figures.

THE POWER STATION; SOME TECHNICAL LIMITATIONS.

The two most important points which to-day limit the size of large power stations are the provision of the necessary cooling water for the steam turbines and the restriction of the total short-circuit power of the generators.

A short numerical survey will be of assistance in arriving at an estimate of the probable size of future power stations. Statistics show that, over long periods, the output of electricity in all countries increases on the average by 10%—15% per annum. It is safe to say that in all highly industrialized countries about 8% of the total yearly growth may be accounted for by the increase in the size of new power stations and about 5% by the greater number of stations altogether in operation. A survey of the larger power stations erected during the last 15 years leads to the following estimate of the probable size of steam stations in the future.

TABLE 1.

Growth of output of power stations over 30 years.

Year	1920	1925	1930	1935	1940	1945	1950
Size of Power Station in MW	100	150	220	330	500	750	1100

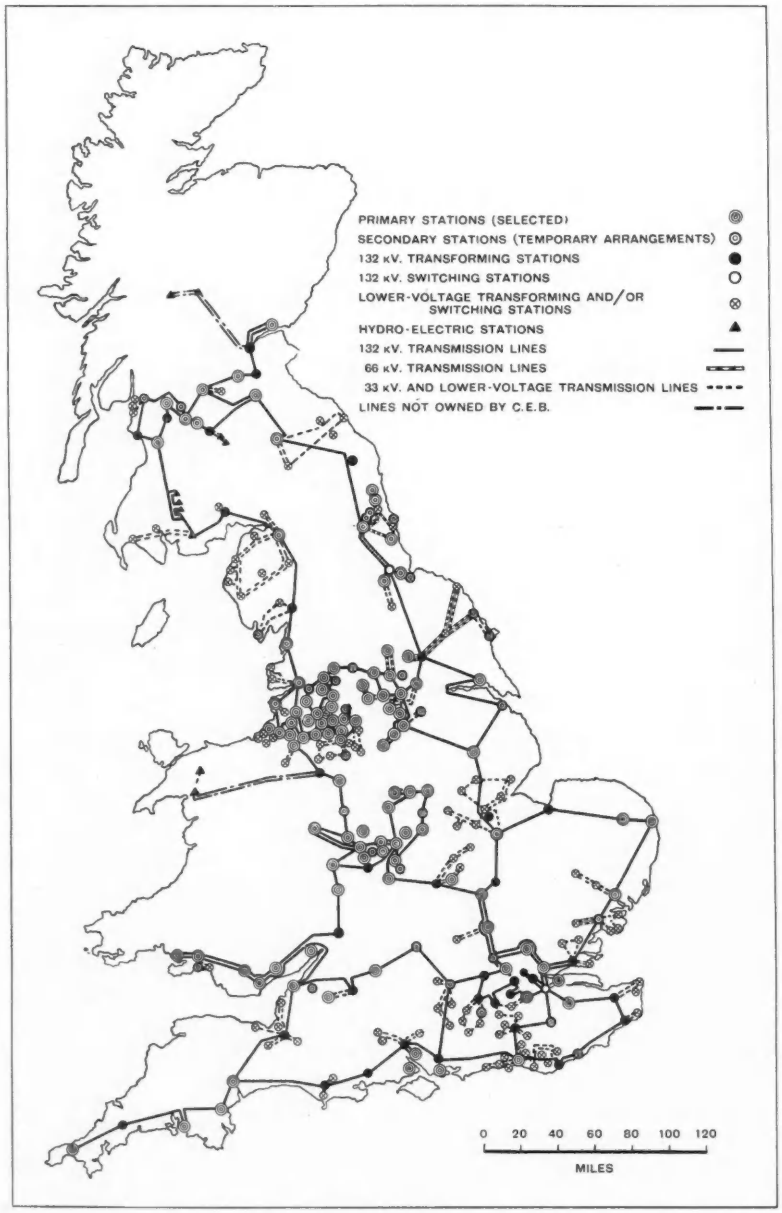

PRIMARY STATIONS (SELECTED)
SECONDARY STATIONS (TEMPORARY ARRANGEMENTS)
132 kV. TRANSFORMING STATIONS
132 kV. SWITCHING STATIONS
LOWER-VOLTAGE TRANSFORMING AND/OR SWITCHING STATIONS
HYDRO-ELECTRIC STATIONS
132 kV. TRANSMISSION LINES
66 kV. TRANSMISSION LINES
33 kV. AND LOWER-VOLTAGE TRANSMISSION LINES
LINES NOT OWNED BY C.E.B.
0 20 40 60 80 100 120
MILES

Fig. 1.—Map of the British Grid.

About $\frac{1}{3}$ to $\frac{2}{3}$ of a ton of cooling water is required for every kWh of energy delivered by the power station, so that, for an output of 500 MW, about 50 to 100 tons of cold water per second will be needed, a quantity that can be supplied only by rivers of considerable size. In order to avoid building large and expensive cooling towers which adversely affect the economical running of the station, both by reason of their cost and moderate cooling temperatures, the tendency in the future, when power stations become still larger, will be to place them on the coast where unlimited quantities of cooling water are readily available. Fortunately most of the important British coalfields are comparatively close to the sea and thus seem destined to supply fuel to the coastal stations of the future.

The short-circuit power being the limiting factor in the size of an individual station, it will be necessary to divide the total power generated amongst 5 to 10 alternators, duly sectionalised by means of cross-reactors or by providing the necessary reactance in the transformers. Further, a steady improvement will be essential in the design of circuit breakers so that, in the event of the failure of a feeder, they will possess the very high breaking capacity necessary to clear the fault with a minimum of delay. The rate of progress in recent years supports the assumption that the growing outputs shown in Table 1 will, in fact, be attained.

Without any further attention to details, therefore, it may reasonably be assumed that a power station of 500 MW can be satisfactorily built up of 6 turbo-generating sets of 83,000 kW each, in the manner indicated diagrammatically in fig. 3.

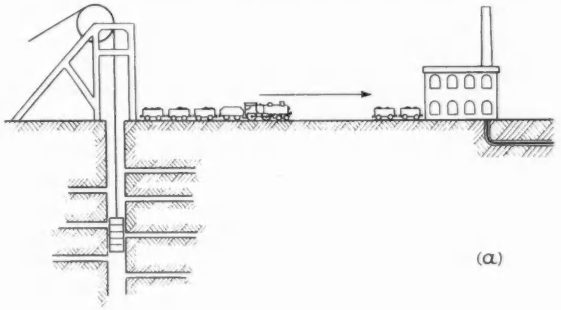
The best size for the transformers depends mainly on the choice of voltage, as it is inadvisable to wind unduly small transformers for very high voltages. In this connection the following table gives an indication of the capacity of each unit for use at very high tension.

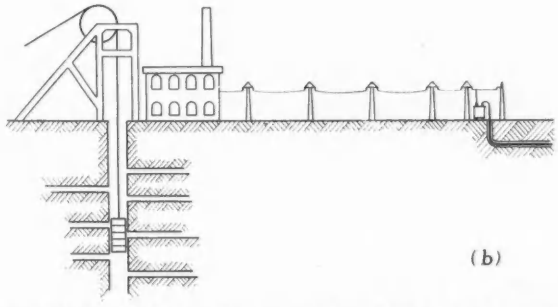
TABLE 2.

Economic output of 3-phase transformers at different voltages.

Voltage in kV	100	120	150	200	250	300
Transformer size in MW ..	15—30	20—40	30—60	50—100	80—160	120—240

Fig. 3 shows diagrammatically the layout of such a station of 500 MW output. There are 6 generators of 83 MW each, paralleled in pairs by 3 three-winding transformers, each of 166 MW capacity, with high reactance between the primary windings.





Figs. 2(a) and 2(b).—Transportation of energy by rail and by electricity.

There is a busbar only on the high voltage side, sectionalised by cross-reactors, leading to three transmission lines of 250 kV.

ECONOMICS OF THE POWER STATION.

The cost of a complete power station can be estimated approximately from average values of the cost per kW of existing stations, though this takes no account of such details as site, nature of soil, the question of cooling towers and so forth. In America the cost is usually taken as $100 to $125 per kW, which is equivalent to £20 to £25 per kW; in

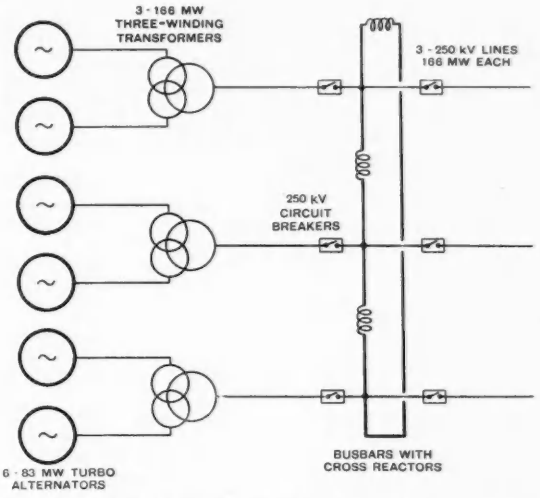


Fig. 3.—Single-line diagram of a 500 MW power station.

Germany the figures lie between RM150 and RM300 per kW, which is £12 to £24 per kW; in England selected Grid stations have cost about £16 per kW. These figures include the primary switching and transforming stations.

It is possible to build a cheaper power station if very high efficiency is not insisted upon for the boilers and turbines. In that case there will be a higher fuel consumption with a corresponding increase in employment in the coalfields. On the other hand, an installation of the highest possible efficiency entails the use of very high steam pressure together with many other features which tend to increase costs. Thus the cost of a 500 MW power station will be as shown in Table 3.

TABLE 3.

Erection costs of a power station of 500 MW output.

Cost in £ per kW	10	15	20
Cost of erection in millions of pounds	5	7.5	10

This is between £5 million and £10 million. For more exact figures it would be necessary to go into considerable detail, which is not possible without fuller knowledge of the particular scheme.

The annual charges in respect of interest, depreciation, operation and maintenance of a big power station are about 15% of the capital invested. The load factor lies mostly between 50% and 60%, and, as a fair average, it may be assumed that the

station is operating at full load for 5,000 hours a year, which is 57% of the possible 8,700 hours. Thus, taking the mean value in Table 3, the capital cost of a kilowatt-hour is :—

$$\frac{15\% \times £7{,}500{,}000}{500{,}000 \text{ kW} \times 5{,}000 \text{ hours}} \times 12 \times 20 = 0{\cdot}108 \text{ pence per kWh.}$$

Table 4 below gives the corresponding figures for the whole range.

TABLE 4.

Capital charges in respect of interest and maintenance for steam power stations.

Erection cost in £ per kW	10	15	20
Capital charges per unit in pence per kWh	0.072	0.108	0.144

Due to more efficient operation the coal consumption of the better power stations has dropped in the last 10 years from 2 lbs. per kWh to about 1·5 lbs. per kWh. With more expensive equipment and high load factors it is possible to reach 1·2 and even 1·0 lbs. per kWh, but it is doubtful whether all stations could be equipped and operated so as to attain these figures. However, if the overall efficiency of power stations continues to improve to the same extent as in recent years, it is possible that 1·0 lb. per kWh will become a more familiar figure in the future.

These figures refer to coal of high calorific value of about 14,000 B.Th.U. per lb. The price of such coal is about 12s.6d. a ton at the pithead, and this figure will be used for purposes of calculation. It must, however, be borne in mind that poorer quality coal has a calorific value of only about 11,000 B.Th.U. per lb., and costs about 9s.6d. a ton at the pithead. Although the price may be strictly proportional to the calorific value it would be relatively much more costly to transport coal of this quality over long distances by rail, whereas if the energy is transmitted electrically it makes no difference whatsoever.

Taking actual figures, the coal consumption of the 500 MW station would be :—

$$\frac{500{,}000 \text{ kW} \times 5{,}000 \text{ hours} \times 1{\cdot}5 \text{ lbs. per kWh}}{2{,}240 \text{ lbs. in a ton}} = 1{\cdot}68 \times 10^6 \text{ tons per annum.}$$

and the cost of this coal is $1{\cdot}68 \times 10^6 \times \frac{12{\cdot}5}{20} = 1{\cdot}05 \times 10^6$ £ per annum.

Table 5 gives values for the whole range, with varying efficiencies of operation.

The cost of coal for the power station considered is therefore of the order of £1,000,000 a year. If this be divided again by 500,000 kW × 5,000 hours or 2,500 × 10^6 kWh, the cost of coal per unit, in pence per kWh, is obtained, as shown in the last line of Table 5.

TABLE 5.

Annual cost of coal for a 500 MW steam power station.

Coal consumption in lbs. per kWh	2.0	1.5	1.0
Total consumption of coal in millions of tons per year ..	2.24	1.68	1.12
Total cost of coal in millions of £ per year	1.40	1.05	0.70
Cost of coal in pence per kWh ..	0.135	0.101	0.067

If fuel cost and capital cost are added together so that the more expensive station is associated with the more efficient operation and *vice versa*, the total prime cost per kWh becomes as in Table 6.

TABLE 6.

Average total prime costs for large steam power stations.

Capital cost in pence per kWh	0.072	0.108	0.144
Cost of coal in pence per kWh ..	0.135	0.101	0.067
Total prime cost in pence per kWh	0.207	0.209	0.211

To find the extreme limits between which these figures may vary the conditions may be reversed when, as shown in Table 7, the ratios do not exceed $\frac{4}{3} : 1 : \frac{2}{3}$.

TABLE 7.

Limiting values of prime costs for large steam power stations.

Capital cost in pence per kWh	0.144	0.108	0.072
Cost of coal in pence per kWh..	0.135	0.101	0.067
Total prime cost in pence per kWh	0.279	0.209	0.139

Even if the assumptions made are not quite exact, it is evident that the cost per unit will certainly not exceed about 0·20—0·25 pence per kWh.

It is interesting to calculate the number of miners to whom a 500 MW station would give employment. In 1936 the average output per man employed in British coal mines was between 250 and 300 tons a year. This takes account of all underground and surface labour including the loading of the coal onto wagons. If the figures from Table 5 are used the results are as shown in Table 8.

TABLE 8.

Number of miners employed in producing coal for a 500 MW power station.

Coal consumption in lbs. per kWh	2.0	1.5	1.0
Number of miners employed ..	8,200	6,100	4,100

The uneconomical power station naturally gives employment to a greater number of miners. The most advantageous balance between greater employment and lower invested capital on the one hand, and high technical efficiency on the other, can be ascertained only by a much more thorough and detailed investigation.

TRANSMISSION LINE; TECHNICAL CONSIDERATIONS.

The most important point in the design of a long, high-tension overhead line is the correct choice of voltage, which depends upon the limited amount of power that each line is capable of transmitting. Three main factors are responsible for this restriction: firstly the cross-section of the conductors which, for mechanical and manufacturing reasons, it is possible to produce, and the resultant ohmic and inductive drop in voltage; secondly the stability of the terminal power stations; and thirdly the losses and the capacitive currents. Here only copper conductors will be considered, the alternative use of steel-aluminium lines being mainly a question of the relative market price of the two metals.

Within the range 100 kV—300 kV the voltages shown in the first line of Table 9 are practicable, the lower figure in each case corresponding to no load, the higher figure to full load, on the generating station. For each voltage the smallest permissible diameter of conductor is given if corona losses and radio interference are to be avoided. The figures of cross-sectional area shown in line 3 assume a stranded conductor up to 150 kV and a hollow conductor above this voltage, experience in high voltage transmission having shown this to be desirable. The values of current given in the fourth line are based on a current density of 1·7 amps per sq. mm. which experience has shown to be an economic figure. This gives a reasonable ohmic drop for transmission over a distance of 160 miles as shown in line 5, where the respective values are given as a percentage of the voltage. The amount of inductive drop tabulated in line 6 indicates that it is not permissible to increase the current further although the tubular section which is used for conductors above 150 kV would allow of this being done.

TABLE 9.

Characteristics of overhead lines and power transmissible at various voltages.

Voltage: kV	100/110	120/132	150/165	200/220	250/275	300/330
Diameter of conductors in mm.	12	15	18	25	30	36
Cross-section in sq. mm. ..	90	140	200	185	250	320
Current in amps.	150	230	340	315	425	550
Ohmic drop; per cent.	13.5	11.2	9.0	6.7	5.4	4.5
Inductive drop; per cent. ..	27	32	40	28	30	32
Power per 3-wire line in MW ..	26	47	88	110	185	280

As a matter of fact, the inductive drop indicates that it would be better to reduce the current at voltages of 120, 150 and 300 kV. The values of three-phase power transmitted, calculated directly from voltage and current, are given in the last line of the table, unity power factor being maintained over the system in all cases.

The mutual stability of the power stations at opposite ends of the transmission line requires that the inductive drop should be still lower. Otherwise, should a disturbance occur, the generators may be pulled out of synchronism. The total reactive drop in both generators, the transmission line and all intermediate apparatus should not exceed 66%. With machines of standard size and construction the reactance of each generator would be at least 12% and of each transformer 10%, leaving an inductive drop of only 22% for the line, a figure that has frequently been verified in practice. This, however, is lower than the values given in Table 9.

Therefore, either the power transmitted must be reduced, in proportion to the reactance, to the values given in Table 10, or an intermediate station must be provided for the sole purpose of supplying wattless power to the line, thus preventing an excessive inductive drop. With a transmission line 160 miles long it is definitely advantageous to make use of such a station and to place it at about the middle of the line, the small expense incurred being amply justified by the increase in the power which can thus be transmitted.

TABLE 10.

Limit of stability of high-voltage overhead lines over 160 miles.

Voltage: kV	100/110	120/132	150/165	200/220	250/275	300/330
Power per line transmissible with stability in MW	22	32	50	90	140	200

In a long transmission line there is an additional loss due to capacitive currents which grow rapidly with length and voltage. However, if it is so arranged that the inductive power due to the reactance of the line and the capacitive power of the charging current neutralize each other, the efficiency of transmission will be a maximum. This is true for only one particular value of power transmitted, and the higher the voltage of the line the greater this becomes. Since inductance and capacitance vary only very slightly with the cross-section of the conductor, this optimum power depends solely on voltage. The values for three-phase lines are given in Table 11, and shown graphically in fig. 4, both for single- and double-circuit lines.

TABLE 11.

Optimum power transmissible per circuit at various voltages.

Voltages: kV	100/110	120/132	150/165	200/220	250/275	300/330
Optimum power transmissible per 3-wire line in MW	27	39	60	110	170	240

All the long transmission lines of the world are working in the near neighbourhood of these values, since every deviation therefrom diminishes the efficiency and stability of transmission. These, therefore, are the figures that must be employed as a basis of calculation, and reference to Table 9 shows that there is still a margin of safety as regards cross-section, which determines the admissible overload of the transmission system.

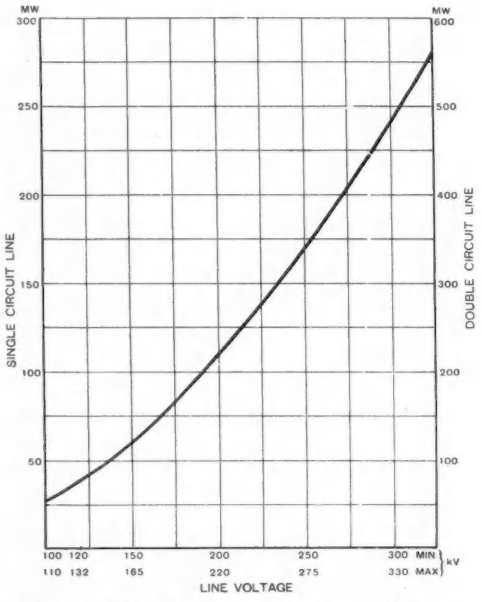


Fig. 4.—Optimum power for transmission.

Since the power that can be transmitted by each three-phase line of three conductors increases rapidly with voltage, the number of lines required to convey 500 MW a distance of 160 miles, in the case under consideration, becomes continuously smaller at the higher voltages. Table 12 gives the exact relative figures, and, in the last line, the actual number of three-phase lines in parallel which are required in practice.

TABLE 12.

Number of circuits necessary for transmission of 500 MW.

Voltage : kV	100/110	120/132	150/165	200/220	250/275	300/330
Number of 3-wire lines	18.5	12.8	8.3	4.55	2.94	2.08
Number of practical lines in parallel	18	12	8	5	3	2

When—perhaps in 1950—it is desired to transmit 1,000 MW over the same distance, twice the number of lines will have to be constructed.

Thus it becomes obvious, in the case being considered, that it is hardly possible to use 110 kV or 132 kV, the lines required being far too numerous ; even the eight lines necessary at 150 kV are rather too many. The right voltage will be at least 200 kV with five lines in parallel, or an even higher voltage, say 250 kV or 300 kV, in order that the operation of the transmission system may not become too complicated by the use of an excessive number of lines.

THE ECONOMICS OF THE TRANSMISSION LINE.

The erection cost of transmission lines increases, of course, with the voltage by reason of the larger cross-section of the conductors required, and also on account of the greater insulation distance necessary both between phases and from phase to earth, which necessitates the use of larger towers. But this is more than counterbalanced by the decrease in the number of lines required, as shown in Table 12. The English Grid with 66 kV 6-wire lines cost about £2,000 a mile, the Scottish Grid with 132 kV 6-wire lines about £3,000 a mile, and the Boulder Dam lines with 275 kV 6-wire lines almost £5,000 a mile. Furthermore, the cost of many existing 3-wire lines is known, and if twice this amount, less a reasonable

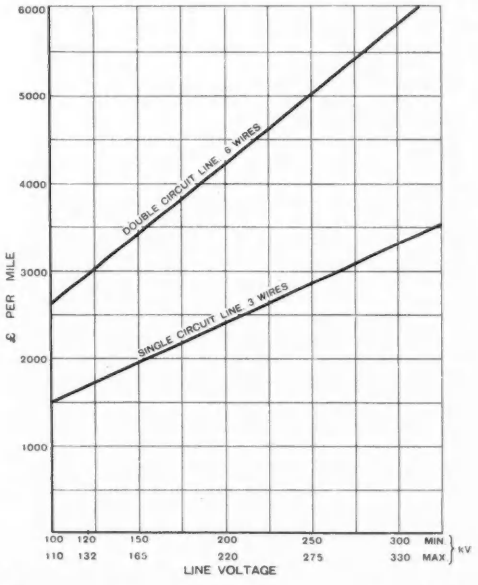


Fig. 5.—Cost of overhead line per mile, single- and double-circuit lines.

discount, be taken as the cost of a 6-wire line, the values so obtained, together with the figures quoted above, form a series which bears an almost linear relation to the voltage, as shown in Table 13.

These figures conform quite closely to the formula:

Cost per mile in £ for double-circuit lines = $1050 + 16 \times kV_{min.}$

This is shown graphically in fig. 5, together with the cost for single-circuit lines.

TABLE 13.

Erection cost of 160 miles of overhead double-circuit lines.

Voltage : kV	100/110	120/132	150/165	200/220	250/275	300/330
Cost of 6-wire line in £ per mile ..	2650	3000	3450	4200	5000	5800
Capital cost of erection in millions of pounds	3.82	2.88	2.21	1.68	1.20	0.93

If the values found from the formula are multiplied in each case by the number of double lines taken from Table 12, then, for a distance of 160 miles, the total expense of erection, in millions of pounds, is obtained, as recorded in the last line of Table 13.

From this there emerges the interesting and most important fact that for such large quantities of power the cost of the transmission lines decreases rapidly and in greater proportion than the increase in voltage. A voltage ratio of 1 : 3 corresponds to a cost ratio of 4·1 : 1. While, for example, the cost of the lines to carry 500 MW at 132 kV would be almost £3 million, at 330 kV it would be less than £1 million.

If these sums be compared with the cost of erection of the power station, which as shown in Table 3 lies between £5 million and £10 million, it becomes evident that the transmission line costs only a moderate fraction of the power station. This is the reverse of what occurs with low tension systems where the power station generally costs less than the conductor network.

With higher voltages the capital cost per annum drops in the same way as the erection cost. A conservative estimate of 3½% for interest, 3% for depreciation, 2½% for maintenance and 1% for administration, *i.e.*, a total of 10% per annum, gives the amounts, in thousands of pounds sterling per annum, shown in the second line of Table 14.

The power losses in the conductors due to ohmic resistance are shown in the fifth line of Table 9 as percentages, these when multiplied by 500 MW give the actual amount of the losses recorded in the third line of Table 14.

Since the optimum power shown in Table 11 is slightly lower than the maximum admissible power which is given in Table 9, and on which the percentage losses were based, there is still a margin of safety of about 10% in these values of loss.

If, as a basis of calculation, the station be again assumed to operate for 5,000 hours a year, and also, to be on the safe side, the cost of generation be taken as high as 10% above the figures in Table 6, namely 0·23 pence per kW, the annual cost of the losses will be as shown in the fourth line of Table 14. The last line then gives the total running cost of the transmission system as the sum of capital and operating costs. It should be noted that these two quantities are almost equal, indicating that, in fact, the lines are being operated at the economic optimum. This verifies the design of the various transmission systems and shows that the relative values of voltage and cross-section have been chosen to the best advantage.

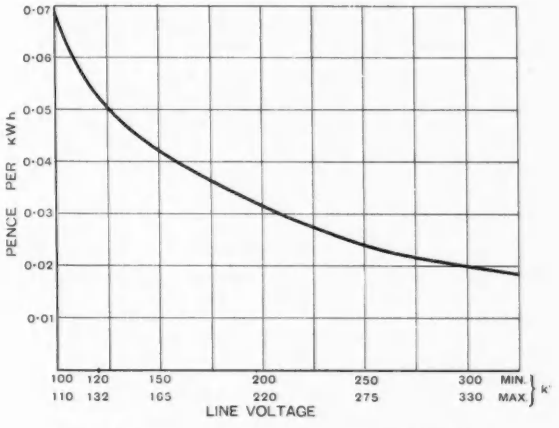


Fig. 6.—Transmission costs over 160 miles.

In practice, with less conservative figures than those assumed here, it may very well be that the cost of transmission will come out anything up to 20% below the values shown in the last line of Table 14, depending on the individual characteristics of each case.

Now it is evident from the last line of Table 14 that the running costs of the transmission system decrease sharply at the higher voltages in the same way as the invested capital. Transmission at 330 kV is almost three times as economical as at 132 kV. This indicates also that for the transmission in question voltages of the order of 200—300 kV must be employed.

No account is here taken of the cost of, and losses in, the transforming stations and intermediate phase-shifting station. Both of these represent only a moderate percentage of the transmission line costs and therefore have no material effect upon the results.

The increase in the price of a kWh due to its

TABLE 14.

Annual cost of charges in respect of capital, maintenance and losses in 160 miles of double-circuit overhead lines.

Voltage : kV	100/110	120/132	150/165	200/220	250/275	300/330
Capital charges in thousands of pounds a year	382	288	221	168	120	93
Transmission losses in MW..	67	56	45	34	27	23
Cost of losses in thousands of pounds a year	321	268	216	163	129	110
Total running costs in thousands of pounds a year.. ..	703	556	437	331	249	203

transmission over a distance of 160 miles at, for example, 220 kV becomes :—

$$\frac{331 \times 10^3 \times 20 \times 12}{500{,}000 \times 5{,}000} = 0{\cdot}0318 \text{ pence per kWh.}$$

For the other voltages the costs are tabulated below. In addition, the curve in fig. 6 has been plotted to permit of interpolation at intermediate voltages.

TABLE 15.

Transmission costs for overhead lines at various voltages.

Voltages : kV	100/110	120/132	150/165	200/220	250/275	300/330
Transmission costs in pence per kWh ..	0.068	0.053	0.042	0.032	0.024	0.020
Percentage of prime cost ..	32	25	20	15	11	9
Minimum power with 6-wire line: MW	54	78	120	220	340	480

Compared with the prime cost of 0·21 pence per kWh shown in Table 6, this, as can be seen from the third line of Table 15, is a fairly small percentage at the upper voltage limit, but is nevertheless considerable at the lower limit.

At this point there emerges one of the most important conclusions to be derived from the whole of this investigation : that the cost of transmitting power over such distances as 160 miles becomes extremely low if very high voltages are used. Naturally full use of such high tensions lines is possible only if sufficient power is available, as indicated in Tables 9 and 11. It is not possible, for instance, to transmit 20,000 or 30,000 kW as cheaply as shown in Table 15. Even 50,000 kW cannot be transmitted a distance of 160 miles at less than about 0·07 pence per kWh. For, if a desirable degree of reliability is to be attained, a double line, at least, will be required, with six conductors either in parallel or in a ring main. Therefore in the last line of Table 15 figures are given representing the minimum amount of power which must be available if the full advantage of this low cost of transmission is to be secured.

Reference to Table 1 makes it evident that present-day requirements are beginning to demand that individual power stations shall be capable of generating 300—500 MW and even more. This means that, from now onwards, sites for power stations may be selected virtually without regard to the situation of the centres in which the power will be consumed. For the transmission cost of about 0·02 pence per kWh over a distance of 160 miles is so low compared with the selling price, which varies all the way from 2d. to 1d. and even down to 0·5 pence per kWh, that it is only one small item in the total account.

These considerations lead to the inevitable conclusion that any country desirous of securing the advantages of this low cost of transmission will have to develop lines, switchgear and transformers suitable for voltages of 200—300 kV.

This by no means implies the supersession of the British Grid at 132 kV, as this will always be very useful for the distribution and exchange of power over wide areas. But it may be more advantageous to feed it with power transmitted at higher voltages from large power stations far outside the main areas of consumption, whenever such an arrangement becomes feasible. On the continent and in North America the trend is also in this direction.

Two general remarks concerning transmission voltages may conveniently be inserted here. In this survey the highest voltage considered is 300 kV, this being the limit of present development. It must be expected, however, that in the future voltages as high even as 400 kV will be attained.

Also, the values of optimum power scheduled in Table 11 are reckoned, in each case, on the basis of the lower of the two voltages given, although the diameter of conductor is equally suitable for the higher one. Therefore the power that can be transmitted may be increased up to 20% without going beyond the range either of highest efficiency or operating stability. There is thus an ample margin in the figures given for the transmission cost per unit.

COMPARISON WITH THE COST OF TRANSPORTING COAL.

It remains to be considered whether the transmission of power electrically over high voltage lines is not more expensive than transporting coal from the mines to a power station situated at the centre of consumption. The relative cost of each will now, therefore, be considered.

The cost of transporting coal by rail varies according to the distance and the various tariffs in operation. In England, the rate per ton is about 3s.6d. for 25 miles, 5s.3d. for 50 miles, 8s.6d. for 100 miles, and 15s. for 200 miles. On the German railways the cost is RM4·30 for 100 km, or 7s. for 63 miles, and RM14·10 for 500 km, or 23s. for 313 miles. These values give an almost linear relation between cost and distance, the curve cutting the axis at 2s. which apparently represents the reloading cost per ton. The figures in Table 16 are fair average values ; the relationship between cost and distance can be expressed by the formula :

$$\text{Cost in shillings} = 2 + 6{\cdot}5 \times \frac{\text{miles}}{100} \quad \text{(fig. 7.)}$$

Thus, for a distance of 160 miles, the average cost will be 12s.6d. a ton.

In consideration of the very large quantities of fuel required by a 500 MW station it may be possible to force down the rate to, say, 10s. a ton. In mountainous districts, on the other hand, it would tend to rise. So as broadly to cover all these possible

variations, three different prices between 10s. and 15s. per ton will be considered.

TABLE 16.
Cost of transporting coal by rail over various distances.

Distance in miles	25	50	100	200	300	400
Cost of transporting coal in shillings per ton ..	3s.6d.	5s.3d.	8s.6d.	15s.	21s.6d.	28s.

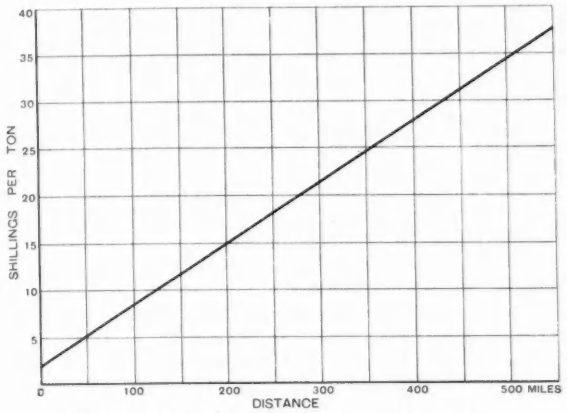


Fig. 7.—Cost of transporting coal by rail.

The total quantity of coal required by a 500 MW power station is given in Table 5 for various degrees of operating efficiency. At the mean value, for example, the cost of transport over a distance of 160 miles would be :—

$$\frac{1{\cdot}68 \times 10^6 \text{ tons/year} \times 12{\cdot}5 \text{ shillings/ton}}{20 \text{ shillings/£}} = 1{\cdot}05 \times 10^6 \text{ £ per year.}$$

or 1·05 million pounds sterling a year; and for the other values, as shown in Table 17 in thousands of pounds sterling.

TABLE 17.
Cost of transporting coal for a 500 MW power station 160 miles by rail.

Transport tariff in shillings per ton		10s.	12s.6d.	15s.	
Coal consumption in lbs. per kWh	1.0	560	700	840	in thousands of pounds per annum
	1.5	840	1050	1260	,,
	2.0	1120	1400	1680	,,

If these figures be compared with the total running costs of the various high tension transmission systems, as given in the last line of Table 14, it becomes evident that only a very low rail tariff combined with an extremely economical power station can compete with electrical transmission at 110 to 132 kV. But even the minimum figure in Table 17, representing the lowest conceivable haulage cost, compares unfavourably with a 150 kV line with an annual running cost of £437,000. However, attention must be confined to actual figures which, at the present time, show that the annual cost of coal haulage is nearer £1,000,000, which cannot compete with the cost of transmission of any of the electrical systems investigated in Table 14. If, for instance, a comparison is made with a 200 kV line, it is seen that the running cost of this is only £331,000 a year, which is exactly a third of the cost of coal haulage, while with a 300 kV line the cost would be only one fifth of it.

A comparison of Tables 14 and 17 demonstrates two additional points :

Firstly that any further improvement in the efficiency of power stations, even should coal consumptions below 1 lb. per kWh be reached, cannot alter the fact of the superiority of high tension lines as a means of transmitting power, particularly if voltages from 200 to 300 kV are employed.

Secondly that if the fuel is to be transported by rail it is out of the question either to use cheaper but poorer quality coal, or to build less expensive power stations of only moderate efficiency, both of which would result in coal consumptions approaching 2 lbs. per kWh and consequently in enormous transportation costs. But with high tension transmission both alternatives are perfectly feasible, which, as already mentioned, enables the relative proportions of capital and labour cost to be varied without unduly affecting the resultant prime cost of generation. Thus with electrical transmission of power, it is possible, though by no means essential, to give employment to more miners than when raw fuel is transported by rail, in which case the coal consumption must perforce be kept down to the absolute minimum.

It is of interest to calculate the increase in the cost of power when the coal is carried by rail and to compare it with Table 15. If the middle line of Table 17 be taken, *i.e.*, a coal consumption of 1·5 lbs. per kWh, the transport cost per unit over a distance of 160 miles will be as shown below in Table 18.

TABLE 18.
Cost per kWh of coal transported 160 miles by rail.

Tariff in shillings per ton	10s.	12s.6d.	15s.
Transport costs in pence per kWh ..	0.0806	0.101	0.121
Percentage of prime cost	38	48	58

These are remarkably high percentages of the prime cost and, in practice, would rule out the use of rail transport over such distances.

No account is here taken of the reloading equipment necessary at each end of the railway line, since both the initial and running costs of such equipment are actually greater than the corresponding costs of a transformer station for the equivalent amount of electrical power. In this respect, too, electrical transmission of power has the advantage.

Moreover, for electrical transmission, all the lines have to be specially erected, while with mechanical transportation advantage can be taken of existing railways. In the latter case, beyond the actual cost of transport, the freight rates have therefore to cover only part of the capital cost.

In this connection it is interesting to see how much of the total traffic on the railway would be accounted for by the transport of the coal required by a power station of 500 MW. Table 5 shows that, with a consumption of 1·5 lbs. per kWh, the amount of coal necessary would be $1{\cdot}68 \times 10^6$ tons a year, which, omitting Sundays, is equivalent to an hourly average of

$$\frac{1{\cdot}68 \times 10^6}{300 \times 24} = 233 \text{ tons}$$

which means twenty-three 10-ton wagons an hour for twenty-four hours a day.

The existing railways would probably be able to handle this amount of traffic without much expansion, but if, as foreshadowed in Table 1, future developments bring into being power stations with outputs of 1,000 MW and even more, and if several of them have to be fed by one set of tracks, then it is improbable that any existing railway could cope with the additional traffic. Under these conditions it might become necessary to lay down entirely new railway lines, and it is doubtful whether the cost of these could be covered by the relatively cheap coal, or "mineral rate," tariff. This is one more argument in favour of building the power station at the pithead and transmitting the power electrically over high tension lines.

Water transport is essentially cheaper, costing only a small fraction of rail transport. Assuming the cost to be between 3s. and 7s.6d. a ton for a distance of 160 miles, and the consumption to be 1·5 lbs. per kWh, the transport charges would be approximately as shown in Table 19.

TABLE 19.

Cost of transporting coal for a 500 MW station 160 miles by water.

Tariff in shillings per ton	3s.	5s.	7s.6d.
Cost of water transport in thousands of pounds per year	252	420	630

Even the lowest of these costs is greater than if the same amount of power had been transmitted electrically at 250 or 300 kV, as can be seen from Table 14. On the other hand, transmission at 132 or 150 kV can hardly compete with the cheap transport of coal by water.

CONCLUSION.

The various economic facts that have emerged in the course of this investigation are summarized in fig. 8. So as to extend the scope of this survey, the relevant distance has been increased to 600 miles, a more appropriate range when countries other than Great Britain are under consideration. Curves have also been added showing the cost of transmission at voltages both higher and lower than those already discussed. So that all the quantities shown in the figure may be readily compared with one another, it

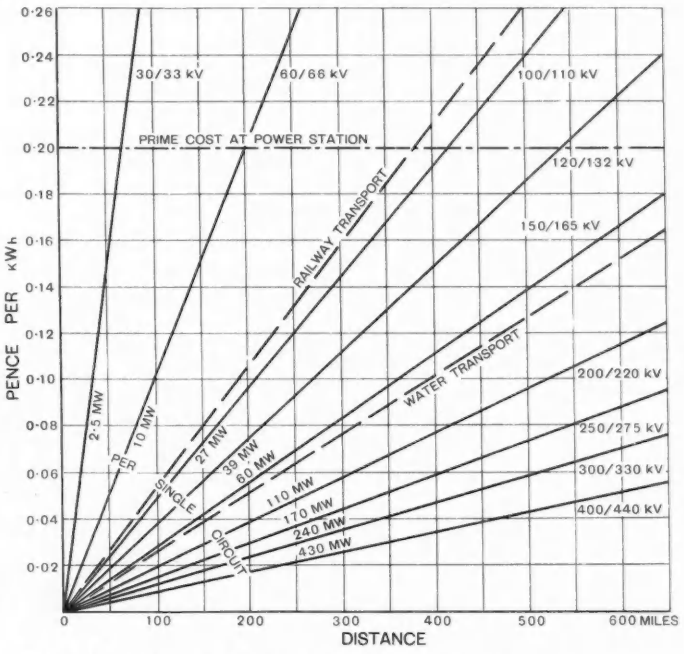


Fig. 8.—Cost of electrical transmission of power with 5,000 hours' operation per annum and 20% charges in respect of interest, maintenance and losses.

has been assumed that in every line the value of energy loss is the same, and equivalent to 10% per annum of the invested capital. The cost of these losses is additional to the capital charge of 10% on account of interest and maintenance, and in both cases the estimate is unquestionably a generous one. As before, a load factor corresponding to 5,000 hours of full-load operation per annum has been assumed, and the cost of erection calculated in accordance with the formula derived from Table 13 for a double-circuit transmission line. For each voltage the optimum value of power that can be transmitted per three-wire line is shown beside the appropriate curve in fig. 8. So as to enable a ready comparison to be made with the cost of electrical transmission, the cost of transporting the equivalent amount of coal by rail or water is indicated by broken lines in the same figure. In calculating the cost of water transport the mean value in Table 19 has been taken, and in fairness to rail transport the constant term in

the formula derived from Table 16, which represents unloading charges, has been dropped, since, in the case of electrical transmission, the relatively small cost of the transformers has also been neglected. In both instances the coal consumption has been taken as 1·5 lbs. per kWh.

Further, a horizontal chain-dotted line has been drawn across the graph in fig. 8 corresponding to 0·20 pence per kWh, which represents the minimum prime cost of generation at the terminals of the steam power station. Hence if the requisite power is available the cost of transmission can be made only a small part of the prime cost, of the order, perhaps, of 10% to 20%.

It is clear from fig. 8 that transmission voltages below 100 kV can be employed to advantage only for comparatively small amounts of power and relatively short distances such as 20 or 50 miles, beyond which the cost becomes unduly high. The use of voltages of 100 to 150 kV increases the economic transmission range from 80 to nearly 150 miles, making it a better proposition than transporting the equivalent amount of fuel by rail. Moreover, with transmission voltages of 200, 300 and even 400 kV the distance may be further extended to from 200 to 500 miles, while still keeping the cost of transmission down to the same small percentage of the prime cost, provided that a sufficiently large amount of power is available.

There are several reasons for the rapid decrease in the cost of electrical transmission of power at higher voltages, even over very long distances. Firstly the fact that the cost of an overhead line does not rise in direct proportion to the voltage, although there may be a considerable increase in the cross-sectional area of the conductors; secondly, that although the line losses are almost proportional to the voltage, the power that can be transmitted increases more rapidly than this, namely, as the square of the voltage.

If, on the other hand, only relatively small quantities of power are to be transmitted over long distances, or if there are any other restrictions on the choice of voltage, the cost will necessarily rise; the actual amount for any given set of conditions can be obtained from the curves in fig. 8.

The main conclusion to be drawn from all that has been said may be stated as follows: in order to transmit any given amount of power over any given distance a definite voltage must be chosen that will give optimum transmission costs, which become progressively lower the higher the voltage that can be used. In view of this it may be asserted categorically that the outlook for the long-distance transmission of large quantities of power is extremely promising—a factor whose influence on the future development of the electrical industry it would be difficult to exaggerate.

REFERENCES.

N. E. Funk. Journal Franklin Inst. Vol. 222, 1936, p. 391.

N. C. Bridge. Journal of the Institution of Electrical Engineers, vol. 74, 1934 p. 37.

R. Rüdenberg. Zeitschr. d. Vereins d. Ingenieure, vol. 76, 1932, p. 649.

Johnstone Wright & C. W. Marshall. Journal of the Institution of Electrical Engineers, vol. 67, 1929, p. 685.

C. W. Marshall. Journal of the Institution of Electrical Engineers, vol. 74, 1934, p. 105.

E. F. Scattergood. Electrical Engineering, vol. 54, 1935, p. 494.

E. W. Smith. World Power, vol. 10, 1928, p. 421.

E. M. Hunter. General Electric Review, vol. 39, 1936, p. 597.

H. L. Samuel and Others. Report of the Royal Commission on the Coal Industry, London, 1926.

Illumination at the Empire Exhibition, Scotland, 1938.

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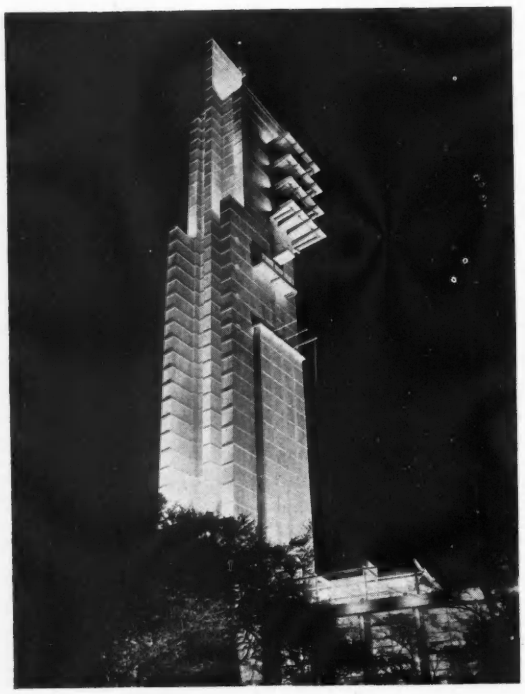


Fig. 1.—The Tower of Empire : the main structure is floodlighted by tungsten floodlights, and the three projecting balconies are outlined in broad coloured bands of red, gold and blue.

INTRODUCTION.

THE extensive equipment which the G.E.C. has installed at the Empire Exhibition, Glasgow, for the lighting of decorative features and the production of special effects, provides one of the most spectacular lighting displays ever seen in Britain. Of the many elaborate installations undertaken, several were planned purely for spectacular effect, while others combine utility with decoration. The schemes include the floodlighting of the exhibition buildings and grounds both in coloured and white light, the colour floodlighting of water displays, the decorative and utility lighting of roads and avenues, the installation of large neon signs and the interior illumination of most of the buildings.

Altogether, the equipment supplied by the Company for the lighting of the Exhibition involves over 4,000 lamps, varying from 15 to 1,000 watts, 1,500 floodlights, 400 ground standards, 3,200ft. of fairy lights, 240 miles of wiring and 20 miles of underground cable. In addition, a considerable amount of switchgear has been supplied for the control of the various installations, together with a large number of accessories.

It is proposed to describe in this article some of the chief exterior illumination schemes which have been undertaken by the G.E.C. in co-operation with Mr. J. Campbell Murray, Consulting Engineer to the Exhibition.

OBSERVATION TOWER.

The Tower of Empire, fig. 1, designed by Mr. T. Tait, of Sir John Burnett, Tait & Lorne, Chief Architect to the Exhibition, is built on a wooded hill which largely dominates the site, and is therefore visible from all parts of the Exhibition. Owing to its height of 280 feet, the tower can be seen from many miles away. The tower is floodlighted on all four sides by a battery of 1000-watt floodlights, comprising medium angle floods and general service lamps which illuminate the lower portion, and narrow beam units equipped with Class B.2 projector lamps for the upper portion. The total load of white floodlighting is 58 kW.

Near the top of the tower are three balconies (each capable of holding 200 people) the fronts of which have been constructed to incorporate high intensity lighting in three colours round the edges. This effect has been attained by means of Osira yellow (sodium), red and light green floodlighting lamps, each lamp being housed in a

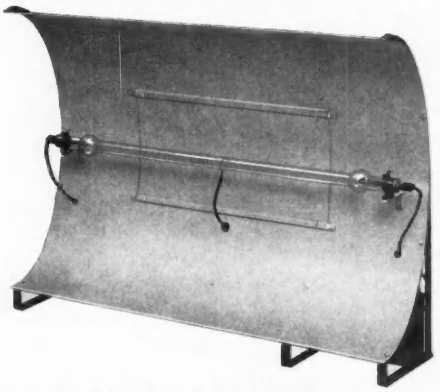


Fig. 2.—Special reflector used on the balconies of the Tower of Empire.

specially designed reflector (fig. 2) which projects the light through prismatic glass panels, giving a band of colour all round the balcony to a depth of 38ins. In all, fifty-four yellow, twenty red and twenty green lamps are used, with a total load of 20 kW.

FOUNTAINS AND CASCADES.

Another particularly spectacular display in the Exhibition grounds is the North Fountain, situated at the foot of the North Cascade opposite the Paisley Road entrance to the Exhibition.

This fountain is built in the form of a circular concrete basin, 52 ft. in diameter, beneath which is the control room housing the pumps and dimming equipment.

The four main jet systems, taking 2,500 gallons of water per minute, are shown in fig. 3. Each system is on a separate piping circuit, the main pipes to which the jets are fitted being of 10in. and 8in. diameter.

The special jets used are particularly worthy of mention, as they add very considerably to the effectiveness of the display. It should be mentioned that the hydraulic equipment was supplied and installed by Drysdale & Co. Ltd., of Glasgow.

Air drawn in at the nozzles gives cohesion to the jet of water so that it rises without "stripping" to a greater height than would be the case with a plain water jet. The induced air prevents drift and the stream of water breaks at the top somewhat like a white plume, owing to the expansion and release of the air, and falls in the form of globules.

This effect is ideal from the lighting point of view as the globules pick up the light, particularly at the plume, with the result that although comparatively low wattages are used for the lighting, the intensity is sufficient to give a brilliantly lit display.

In spite of the large amount of space in the 52-feet diameter pool, a considerable amount of careful arrangement was necessary to accommodate the jets, pipes, floodlights and cable runs, and some idea of the

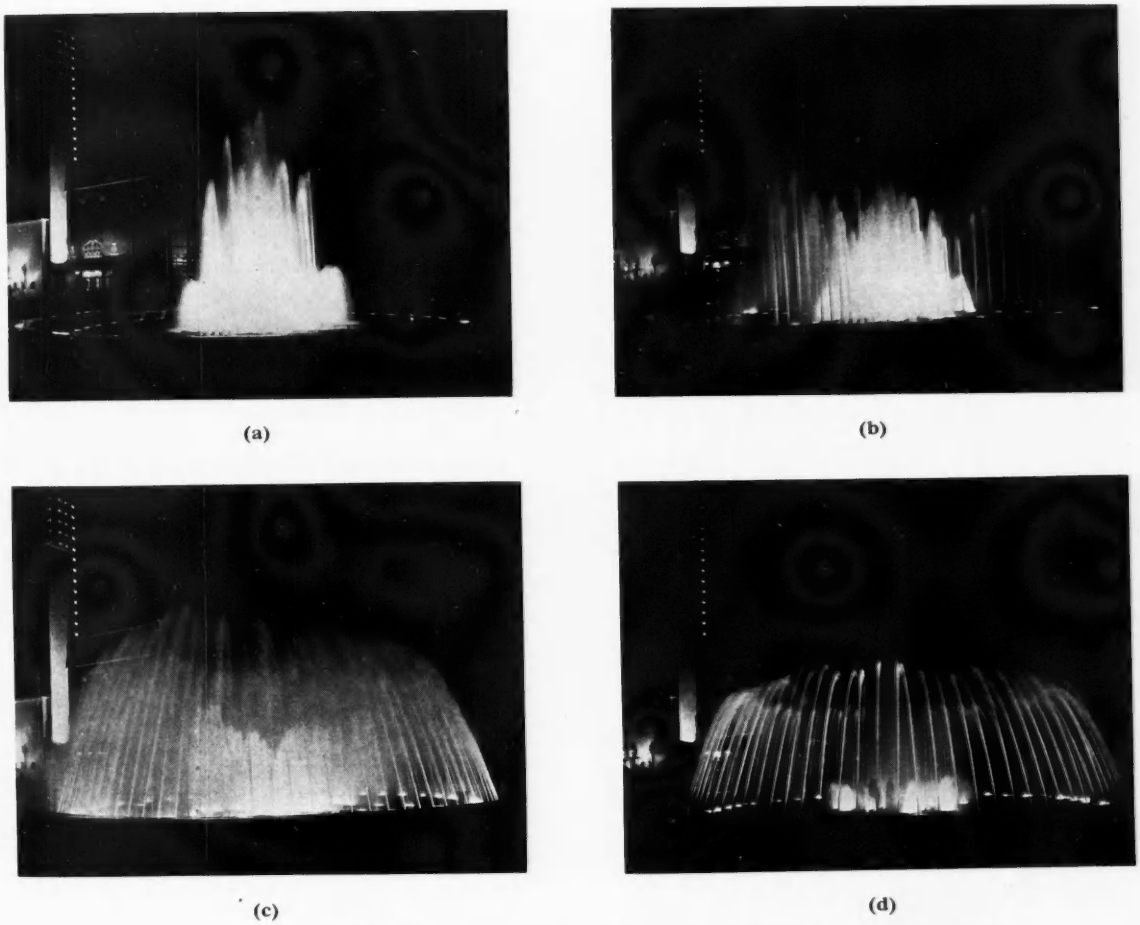


Fig. 3.—Alternative jet formations of the North Fountain. A total of 372 floodlights is used to produce the colour effects in this fountain (see figs. 4 and 5).

Fig. 4.—North Fountain basin showing the large number of special underwater floodlighting units installed.

quantity of apparatus required and the manner of its disposal may be gathered from fig. 4, which shows a portion of the fountain basin with the central jets and floodlights in the foreground, while fig. 5 shows a general plan of the fountain. In all, there are 372 floodlights in the pool, and special equipment had to be designed for the purpose, a typical unit being shown in fig. 6.

These units are made in triple- and single-reflector form, arranged to house red, green and amber colour screens in the case of the triple-reflector, the single type being used without a colour screen for white illumination.

The operation of each of the four jet systems is automatically controlled by hydraulically operated sluice valves, the automatic control gear also working the master switches controlling the dimmer for the floodlights. The water effects are arranged for alteration every half-minute, and the lighting every five seconds, the complete cycle taking twenty minutes.

The four sluice valves controlling the jets are connected by pipe lines to four pilot valves operated by tappets and cams, which are driven by a motor. The pilot valves are connected mechanically to

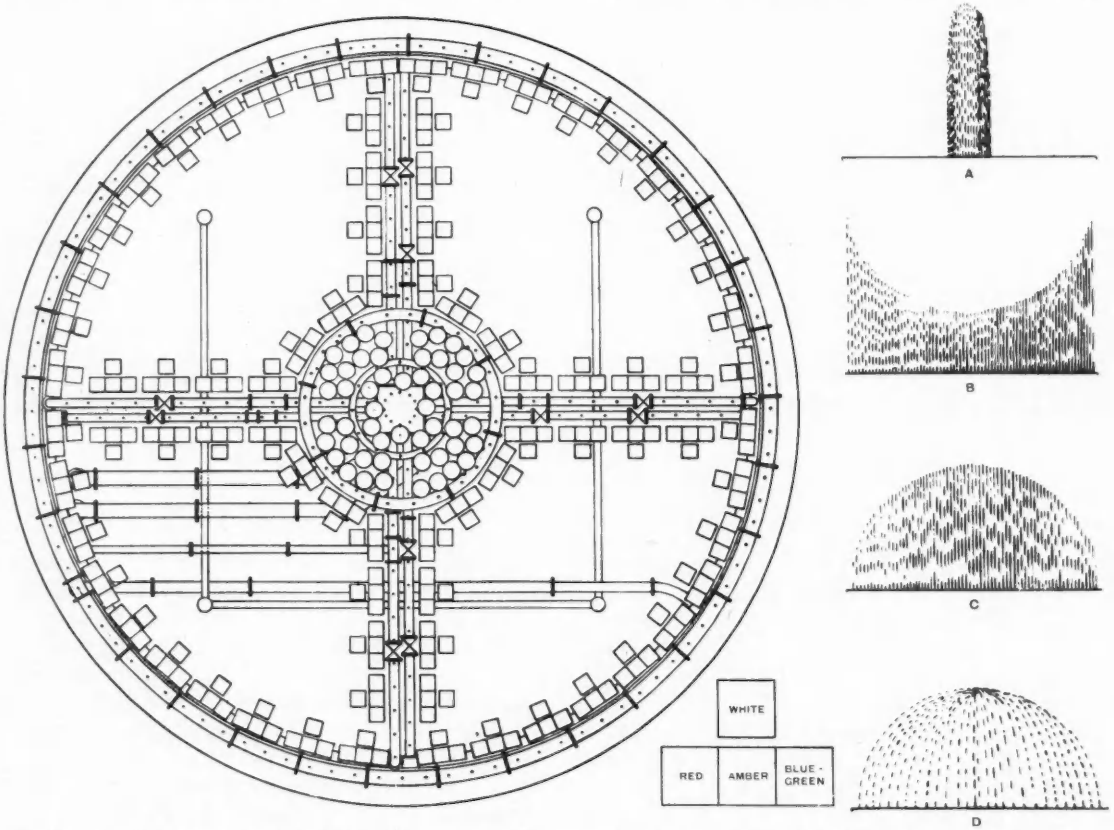


Fig. 5.—Plan of North Fountain showing arrangement of underwater floodlighting units seen in fig. 4. On the right are shown the various jet formations, some of which are shown in fig. 3.

mercury switches, which provide an impulse to a relay and close a contactor controlling the master drum on the dimmer, which in its turn energises a number of multi-contact relays. These feed the current through the cycle drum to the selected dimmers.

The dimmer (see fig. 7) measures 7ft. long by 3ft. 9in. wide by 6ft. high, and the dimmer arms are operated by means of magnetic clutches, one clutch being used to raise and another to dim. Limit switches are fitted to cut out the clutches at the end of travel.

The magnetic clutches consist of arms freely mounted on a shaft on either side of a revolving wheel fixed to the shaft, and on each of these arms is fitted a magnet coil which when energised in the manner described is attracted to the face of the wheel, thus transmitting the drive to the dimmer through a connecting link fitted at the top end of

Fig. 6.—One of the underwater floodlighting units.

the arm. One link is connected to the dimmer above the axis of the shaft and another below, thus imparting a forward or a reverse motion to the dimming arm, according to which clutch is energised.

The shaft on which the magnet wheels are fixed revolves continuously and is coupled by chains and sprockets to the main driving motor. A further motor is used for accelerating the dimmer for the purpose of rapidly resetting the dimmer on to a new cycle after a given jet system is cut off, so that when another jet system comes into operation a new colour combination is obtained. The magnets and relays of this equipment are arranged to operate on 15 volts D.C., a motor-generator being provided for this purpose.

The water level in the pool by day is such that the whole of the floodlighting equipment is submerged and no unsightly effect is obtained. At dusk the level is lowered until the tops of the floods are just above water. In this way, the full intensity of the lighting effect is obtained without the considerable diffusion which results if the light is projected through the water.

On the hillside above the North Fountain is the

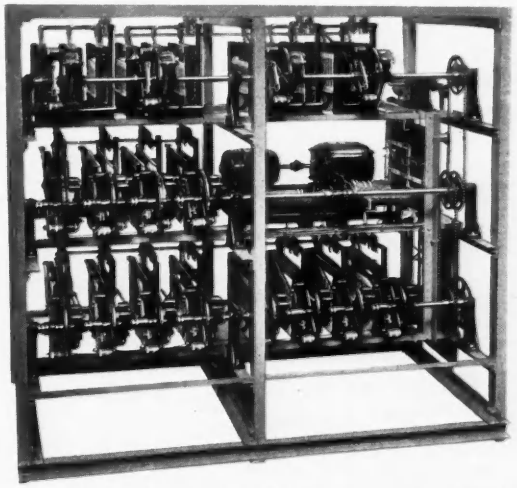


Fig. 7.—Electrically operated dimmer used in conjunction with the colour floodlighting of the North Fountain.

North Cascade, fig. 8, which begins near the summit of the hill and terminates in the North Fountain. The whole construction extends about 550 feet down the hillside and the water falls through a total height

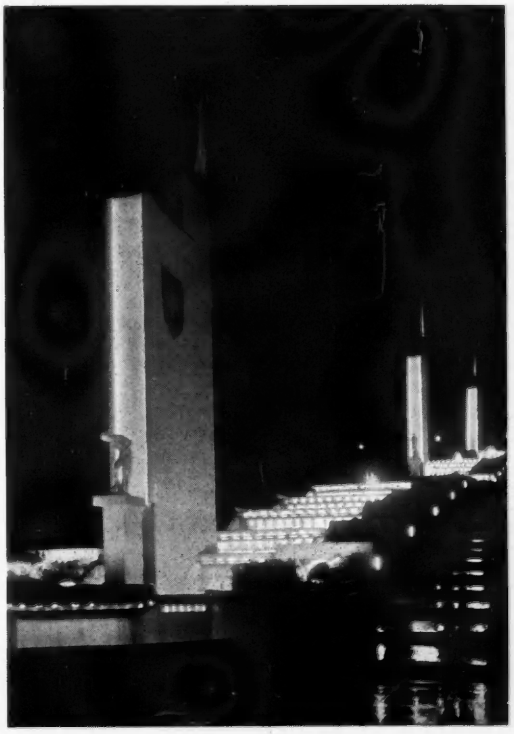


Fig. 8.—The North Cascade: cascades of water are floodlighted from underneath in changing, intermingling colours. It takes 12 minutes before any colour effect is repeated.

Fig. 9.—One of the floodlighted pylons of the North Cascade.

of 75 feet. The complete display consists of three similar units, each comprising six rectangular and two circular pools, from each of which the water falls as a cascade 15 feet wide. The falling water streams over glass weirs, ribbed on top to give turbulence and designed equally to reflect the sunlight by day and transmit the coloured lighting at night.

A decorative pylon, 20 feet high, fig. 9, placed at the lower end of each section, is illuminated by means of floodlights set in the flower beds on either side, while on the front a life size plaster figure is silhouetted against a vertical cove illuminated from concealed lights.

At each side of the falling water, flower beds are formed, and outside these are stairways, each 15 feet wide. Inclined "fish-tail" jets are let into the concrete structure at the summit of each unit of the cascades, and vertical "feather" type jets in the pools. Altogether 2,200 gallons of water are in circulation, supplied by a pump of 130 h.p.

The cascading water is illuminated by means of 48 colour-sprayed lamps in four colours, concealed under each glass weir, and the face of the waterfall below the weir is covered with specially bent figured mirror glass in order to pick up the light from the lamps and reflect it through the water, at the same time imparting a sparkle to the water during the daytime. The "feather" jets in the pools are each illuminated by four 500-watt floodlights burning under the water, red, green, amber and white being used, while the "fish-tail" jets are each lit by a 300-watt white floodlight.

Fig. 11.—Facade floodlighting of the main entrance to the Palace of Engineering.

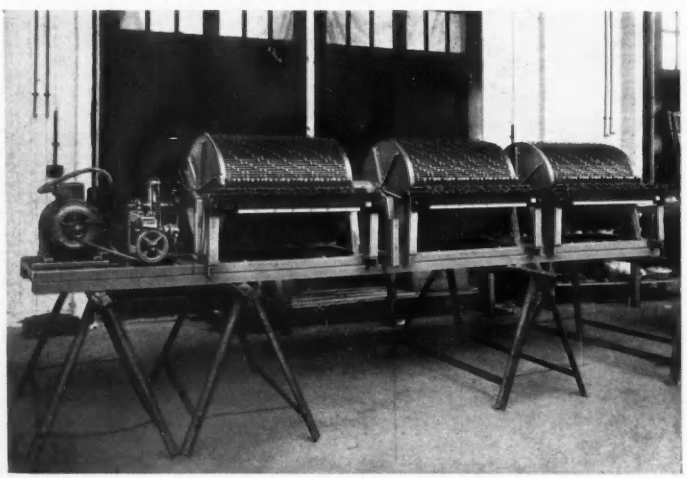


Fig. 10.—The flasher used in conjunction with the colour floodlighting of the North Cascade.

The lighting is automatically controlled from the pumping chamber below the North Fountain by means of a special multi-way flasher shown in fig. 10. This flasher consists of three circular drums, mounted in tandem on a shaft carrying in all about 6,000 studs to operate the 84 tilting mercury switches. The drums are driven by a motor connected to a pawl-and-ratchet wheel, which revolves the drums intermittently, so that each circuit is made for 10 seconds. The individual colours remain on for ten seconds,

the complete cycle taking 40 seconds. Each cycle repeats three times before giving place to the next, and there are six cycles altogether. The master cycle takes 12 minutes to run through before repeating, but a change of colour takes place every five seconds.

The South Cascade is similar in arrangement to one of the units of the North Cascade, but the pools are larger. About 1,200 gallons of water are circulated by a 30 h.p. motor, and the lighting is similar to the North Cascade, but the flasher has only one drum instead of three.

FLOODLIGHTING OF BUILDINGS.

Nearly all the buildings in the Exhibition Grounds are floodlighted by G.E.C. white floodlighting units.

Fig. 13.—Special fittings mounted on the flag-poles provide light in upward and downward directions.

Fig. 12.—One of the main entrances to the Exhibition Grounds.

The largest of these buildings is the Palace of Engineering, which covers roughly the same area as Buckingham Palace. The impressive facade above the entrance has been built in the form of six pillars, each about 15 feet apart, with a height of approximately 40 feet from the level of the top of the steps to the soffit. Behind each of these pillars is placed a floodlight housing a 400-watt high pressure mercury vapour lamp, burning horizontally without deflector and lighting the soffit above and the windows behind the pillars, thus throwing the pillars into silhouette against the illuminated background. The effect is shown in fig. 11. While, generally, it was agreed that white floodlighting only should be employed for the illumination of buildings throughout the Exhibition, an exception was made in this instance on account of the fact that the blue-green light of the mercury vapour lamps toned with and emphasised the blue-green colourings of the building.

Fig. 14.—Another effective example of facade floodlighting: the Palace of Industry, North.

The entrances to the building are illuminated by means of a large number of architectural lamps mounted on the underside of the canopy, resulting in a high intensity of illumination which, combined with the characteristic colour of the floodlighting above, give an effect of balance to the whole of the facade.

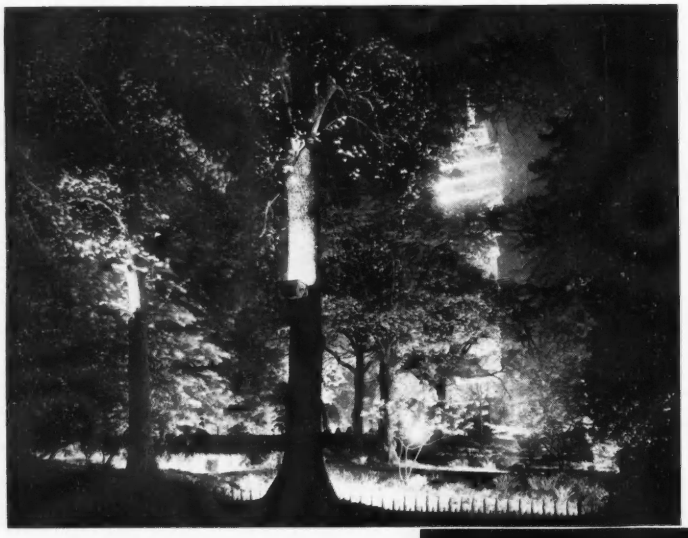


Fig. 15.—Floodlighting of the tree tops and the gardens of the Exhibition.

The Palace of Industry West, the second largest building, and the Palace of Industry North, fig. 14, are two other notable buildings which are floodlighted in white, while other floodlighting installations include the Concert Hall, the Scottish Pavilions, the Palace of Arts and the Colonial Pavilions.

Above each of the two main entrances to the Exhibition Grounds is a Scottish lion outlined in neon tubing. These lions are 8ft. 6ins. high and are enclosed in three rings of blue neon tubing. Two-colour Claudegen neon tubing is employed in the treatment of four decorative pylons each 50ft. high.

CLACHAN.

An interesting feature of the Exhibition is the Clachan including the big house, inn and cottages, with a burn which terminates in a small loch.

The floodlighting is carried out by means of a number of 300-watt floodlights illuminating the main features of this exhibit, and a considerable amount of experimental work was necessary to determine the most suitable positions for the floodlights, owing to the difficulty in concealing them from the view of the public walking along the pathways. The desired result was achieved finally by screening the floodlights behind trees and bushes as far as possible, and directing the light in such a way that no objectionable glare was caused.

GENERAL OUTDOOR ILLUMINATION.

The Mosspark Boulevard entrance of the Exhibition (fig. 12) is of some interest from the lighting point of view. It is built in the form of a canopy over the pay boxes, surmounted by ten pillars each about 25 feet high by 8 feet wide, carrying a formation of slats or ribs along the top. The vertical sides of these pillars, together with the slats or ribs above, are floodlighted by yellow sodium floodlights placed on the canopy, one on either side of each pillar, making a total of 20 floodlights, with a loading of 2,000 watts.

The lighting of the numerous flags on poles throughout the Exhibition grounds has been carried out in a novel manner. Approximately 15 feet above the ground a special fitting in the form of a truncated cone 4ft. in diameter is fixed to the pole. The fitting is made in two halves with arrangements inside for clamping to the pole so that the joint is not readily visible from ground level. Each fitting is arranged to accommodate two narrow-angle aluminium reflectors for 300-watt general service lamps with a heat-resisting cover glass over each reflector for protection from the weather. The bottom of the fitting is glazed with

Fig. 16.—A corner of one of the Scottish pavilions, showing the illuminated cascades on the left.

bent flashed opal glass lit by six 60-watt lamps which serve to give a certain amount of illumination on the lower part of the pole and the ground below, fig. 13.

The King's Way leading from the Concert Hall to the Colonial Avenue is almost entirely lit by indirect means, the type of fitting used being shown in fig. 14. These fittings are built up in the form of a series of aluminium cones painted matt white, the largest measuring four feet in diameter with three smaller cones underneath it. Illumination of the underside of the cones is carried out by forty lamps totalling 1140 watts, the lamps being housed inside the three cones, while the lower cone is lit by installing the lamps in a bowl-shaped reflector beneath. The whole fitting is supported on a steel pole 20 feet above the ground, and although the lighting is entirely indirect, it is quite sufficient to illuminate the thoroughfare. Other main avenues are lit by smaller fittings of the same type.

Fig. 18.—A striking lighting feature above the South Cascade.

Fig. 17.—The Palace of Industries, which covers 2½ acres, picked out by floodlights.

As previously mentioned, the Exhibition Grounds are dominated largely by a wooded hill about 100 ft. higher than the surrounding land, and the area covered by the trees is bordered by a main roadway. The trees by the side of this roadway can be seen from a considerable distance so that it was desirable that the tops of the trees should be well illuminated in addition to the lower branches.

The inner trees are shielded from long range vision, and can be seen only by those walking immediately beneath them, and it was therefore necessary to light only the underside of the foliage.

With this aim in view it was decided to surround the area covered by the trees with floodlights, using 125-watt high pressure mercury vapour lamps, with the light directed up the hill towards the trees, so that no direct light is visible from the surrounding landscape. Mercury vapour lamps were selected owing to their ability to bring out the natural colour of the foliage. The inner trees are illuminated by floodlights, using 200-watt tungsten filament lamps fixed to the trunks of the larger trees about 15 feet above ground level (fig. 15) and tilted horizontally so that no direct light from the floodlights can be seen from below.

The remaining lighting equipment, includes many standard commercial pattern floodlights for the illumination of the principal Exhibition buildings; decorative standard units for the lighting of the roadways, and concealed lighting units for the flower beds in the main avenues and on the steps above the South Cascade (fig. 18), leading to the Garden Club.

The Electrification of Jarrow Tube Works.

By WILLIAM SCOTT
Managing Director of Jarrow Tube Works, Ltd.

Jarrow Tube Works was opened officially on May 27th by the Duchess of Northumberland, and for some months has been in successful commercial production.

In planning this new works, it was determined that the plant should embody the very latest developments in tube mill equipment, and thus it is of great interest that electricity is used on an unusually large scale. This article describes the most prominent features of the electrical installation.

INTRODUCTION.

THE solid drawn or weldless steel tube was first introduced about 50 years ago, but for many years little progress was made in the methods of its production. During the past ten years, however, considerable improvements have been made, with the result that equipment is available which enables a better quality product to be manufactured at a lower cost. Full advantage was taken of these improvements in selecting the equipment for Jarrow Tube Works in order that it should be capable of producing tubes of outstanding quality.

The plant is designed for the manufacture of hot finish, cold drawn, weldless tubes to fine limits, and bright annealed tubes up to 3½ inches outside diameter.

BUILDINGS AND LAYOUT.

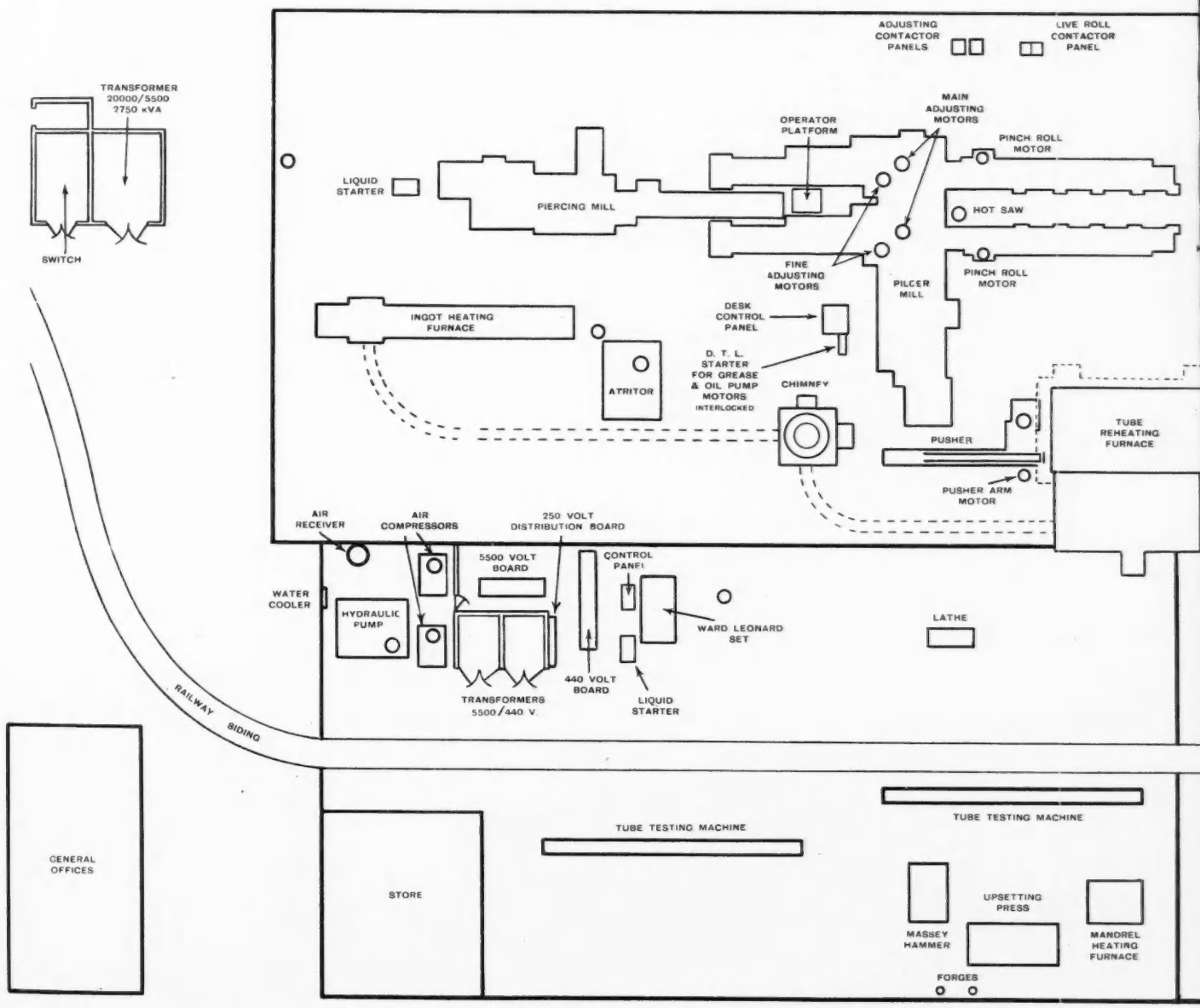
The main buildings consist of two bays, that which accommodates the mill being 540 feet long, 90 feet wide, and 20 feet in height to the eaves. The adjoining bay is 500 feet long by 75 feet wide, most of the available area being equipped for maintenance work, manipulation plant and warehouse purposes. One section, however, is reserved for electrical control and distribution equipment, an air compressor plant and a hydraulic pump. The layout of the principal items in the plant is given in the plan at fig. 1, and a view down the mill in the frontispiece, p. 232. The buildings are very spacious, well lighted and well ventilated.

The convenience of the layout is a marked feature of the mill, and in consequence a rapid and smooth flow of work is maintained.

MILL EQUIPMENT.

The hot mill plant consists essentially of two Pilger mills and a reducing mill. The Pilger mill equipment comprises billet furnace, piercing mill, two-stand Pilger mill with two feeding equipments and two sets of runout apparatus, two hot saws and a cooling bank. The reducing mill plant comprises re-heating furnace, reducing mill, hot straightening machine and cooling bank. All these items of mill

Fig. 2.—Pilger Mill equipment, showing to the left the desk control pillar, with direct-to-line starters for auxiliary motors.


TRANSFORMER
20000/5500
2750 kVA
SWITCH
ADJUSTING CONTACTOR PANELS
LIVE ROLL CONTACTOR PANEL
MAIN ADJUSTING MOTORS
OPERATOR PLATFORM
PINCH ROLL MOTOR
LIQUID STARTER
PIERCING MILL
HOT SAW
FINE ADJUSTING MOTORS
PILGER MILL
PINCH ROLL MOTOR
INGOT HEATING FURNACE
DESK CONTROL PANEL
D. T. L. STARTER FOR GREASE & OIL PUMP MOTORS INTERLOCKED
ATRITOR
CHIMNEY
TUBE REHEATING FURNACE
PUSHER
PUSHER ARM MOTOR
AIR RECEIVER
AIR COMPRESSORS
250 VOLT DISTRIBUTION BOARD
5500 VOLT BOARD
CONTROL PANEL
WATER COOLER
HYDRAULIC PUMP
WARD LEONARD SET
LATHE
TRANSFORMERS 5500/440 V.
440 VOLT BOARD
LIQUID STARTER
RAILWAY SIDING
GENERAL OFFICES
STORE
TUBE TESTING MACHINE
TUBE TESTING MACHINE
UPSETTING PRESS
MASSEY HAMMER
MANDREL HEATING FURNACE
FORGES

JARROW TUBE WORKS

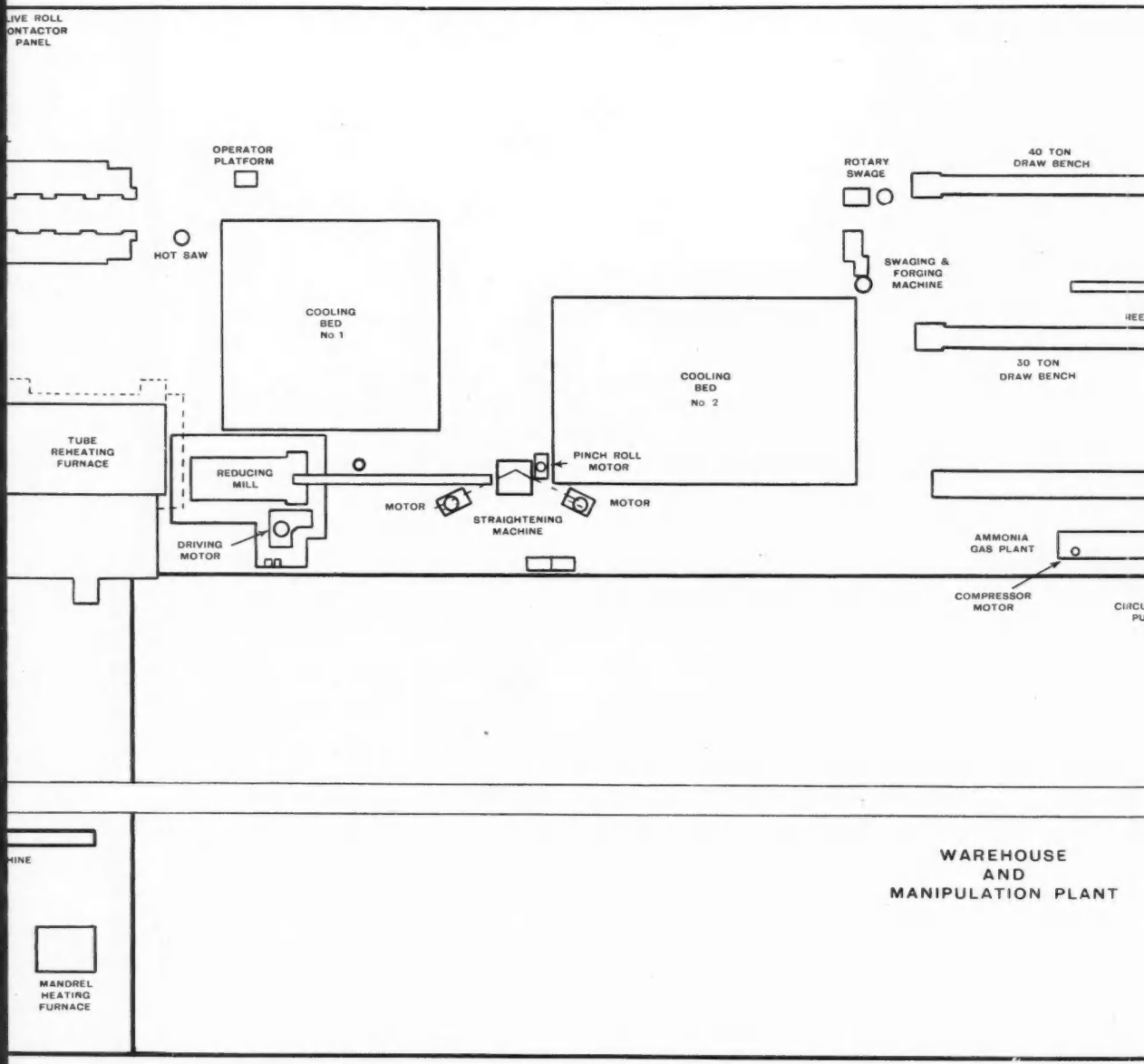
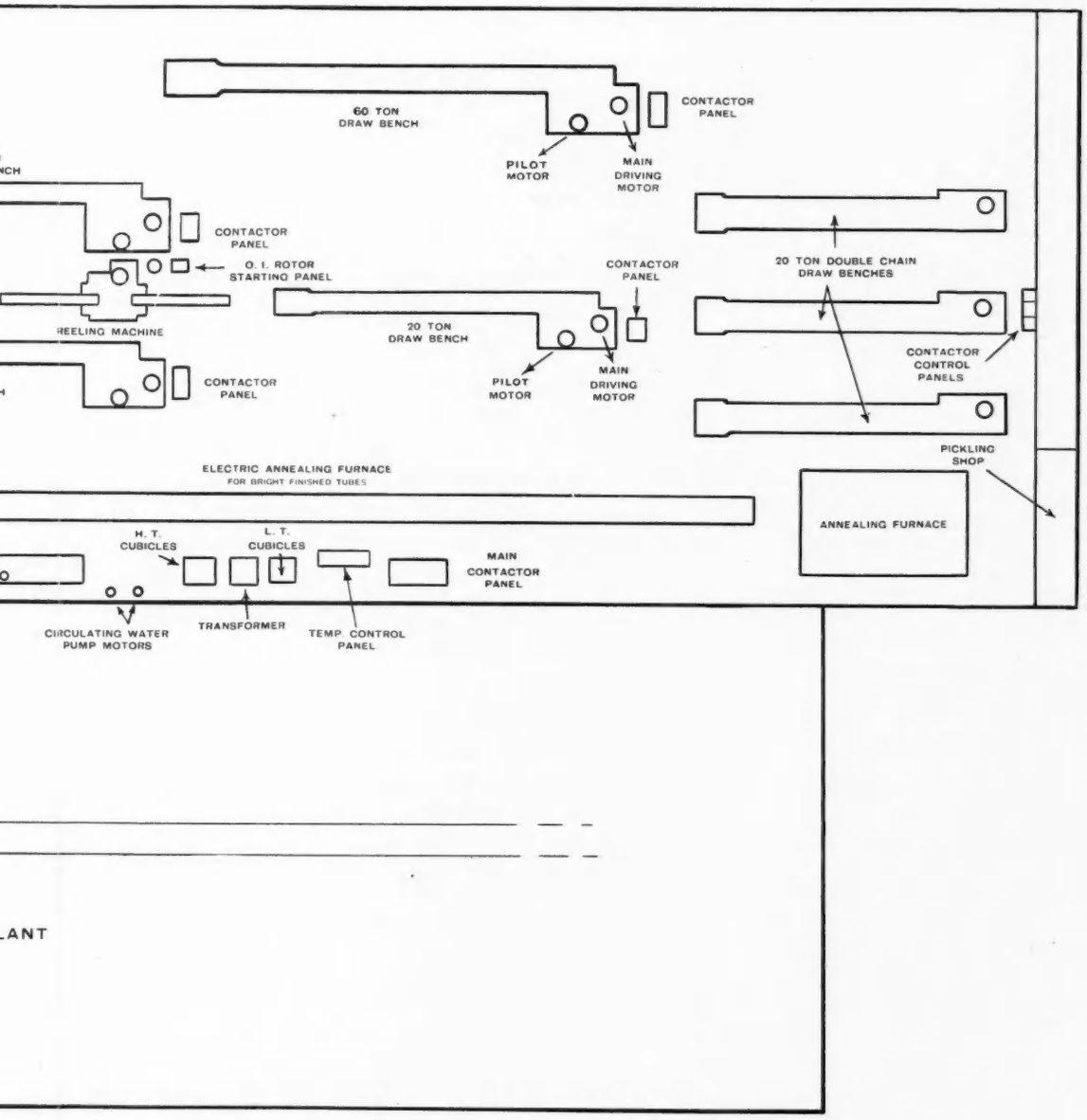


Fig. 1.—General plan of main rolling mill bay at Jarrow Tube Works.


60 TON
DRAW BENCH
CONTACTOR
PANEL
PILOT
MOTOR
MAIN
DRIVING
MOTOR
CONTACTOR
PANEL
O. I. ROTOR
STARTING PANEL
REELING MACHINE
CONTACTOR
PANEL
20 TON
DRAW BENCH
CONTACTOR
PANEL
PILOT
MOTOR
MAIN
DRIVING
MOTOR
20 TON DOUBLE CHAIN
DRAW BENCHES
CONTACTOR
CONTROL
PANELS
PICKLING
SHOP
ELECTRIC ANNEALING FURNACE
FOR BRIGHT FINISHED TUBES
ANNEALING FURNACE
H. T.
CUBICLES
L. T.
CUBICLES
MAIN
CONTACTOR
PANEL
CIRCULATING WATER
PUMP MOTORS
TRANSFORMER
TEMP. CONTROL
PANEL

LANT

equipment are shown in the illustrations, figs. 2, 3, 4, 9, 11 *et seq.*, to which more detailed reference will be made later in this article.

If hot drawn tubes of diameters from 2 inches to 3½ inches are required, they can be produced by the Pilger mill, the tubes on passing from the mill being taken to a hot saw for cutting to the specified lengths, and thence to cooling bed No. 1, fig. 3. If, however, tubes of lesser diameter are needed, they are taken *via* the re-heating furnace to the reducing mill, which consists of eight stands, and is capable of producing tubes down to one inch in diameter. From the reducing mill the tubes are passed through a straightening machine of the cross roll type, fig. 4, and thence to cooling bed No. 2.

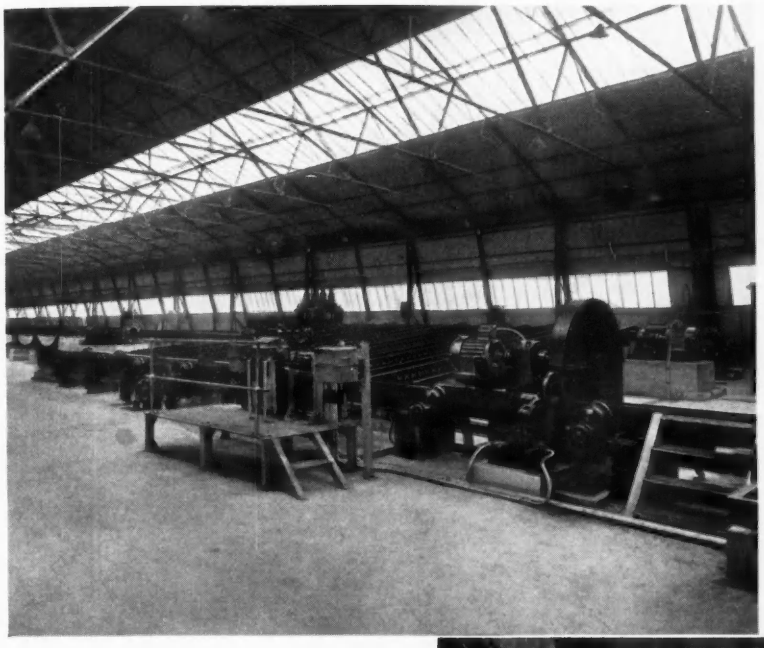


Fig. 3.—Cooling bed No. 1, driven by 13½ h.p. cowl-cooled slipring motor. In the foreground is a 20 h.p. 1,450 r.p.m. squirrel cage motor driving a hot saw. One of the auxiliary motor control platforms is shown in the centre.

The very highest quality tubes are finished on cold drawbenches, nine of these units being already installed, while more are being added. The hot rolled tubes are drawn through dies, over plugs and mandrels, which are machined to very fine limits. By this method the accuracy of the tube diameter can be guaranteed to within a few thousandths of an inch. The operation also exposes the slightest defect in a tube. In view of the heavy work put upon the tubes by this operation, it is necessary for them to be re-annealed between passes in an annealing furnace.

If required, bright annealed cold drawn tubes can be produced through the operation of an electric continuous bright annealing furnace in which a controlled atmosphere is employed. This furnace is unique in its application.

ELECTRICAL EQUIPMENT.

Throughout the works electricity is used on a most lavish scale, which accounts for the extensive and varied nature of the electrical plant and equipment which have been installed. It comprises the transformers and switchgear for main distribution and control purposes, large electric motors for driving the mills, smaller motors with a total capacity of 1,500 h.p. for driving auxiliary machinery, motor control gear, the continuous bright annealing furnace, lighting fittings and lamps, high and low tension cables and auxiliary distribution switchgear.

Fig. 4.—Straightening machine driven by two 20 h.p. slip ring motors ; also is shown 10 h.p. pinch roll motor.

The whole of this equipment was manufactured and supplied by The General Electric Co., Ltd.

The Pilger mill is driven by a 540 h.p. D.C. motor, which is Ward-Leonard controlled ; the piercer mill and reducing mill are driven by slipring induction motors of 720 h.p. and 135 h.p. capacity respectively.

MAIN DISTRIBUTION AND CONTROL SCHEME.

The following is a description of the main distribution and control scheme.

The electric supply to the works is from the mains of the North Eastern Electric Supply Co. Ltd., through a 2,750 kVA, 20,000/5,500 volt transformer in the company's substation on the works' site, fig. 5. Power is taken thence to a 6-panel S.V.D. type switchboard, fig. 6, situated in the works' main electrical control room. Other equipment in this room consists of a nine-panel, 440 volt pedestal, oil-immersed, draw-out type board, a Ward-Leonard motor-generator set which supplies the Pilger Mill main motor, and the control panels for this set. A view of the control room with the Ward-Leonard set in the foreground is shown in fig. 7.

The S.V.D. switchboard panels control: (1) the 5,500 volt incoming line from the 2,750 kVA transformer; (2) the piercer mill motor; (3) the motor of the Ward-Leonard set; (4) and (5) two 450 kVA transformers, and (6) a 220 kVA transformer supplying the continuous bright annealing furnace. Each of the panels is equipped with a 300 ampere oil circuit breaker with a breaking capacity of 75,000 kVA, ammeter, current transformer, etc. In addition the first panel is provided with a voltmeter, panels 2, 3, 4, 5 with watthour meters, and panel 2 also with a recording wattmeter.

The 450 kVA transformers supply the 440 volt current to the works for the auxiliary motors and for lighting. They are accommodated in an annexe to the main control room and are shown in fig. 8. The 440 volt system is controlled from the pedestal oil-immersed switchboard, the individual units controlling respectively: Nos. 1, 2 and 3, 200 h.p. outgoing feeders for small motors; Nos. 4 and 5, the L.T. sides of the 450 kVA transformers; No. 6, 50 kVA lighting circuits, and Nos. 7, 8 and 9, individual large motors or groups of large motors.

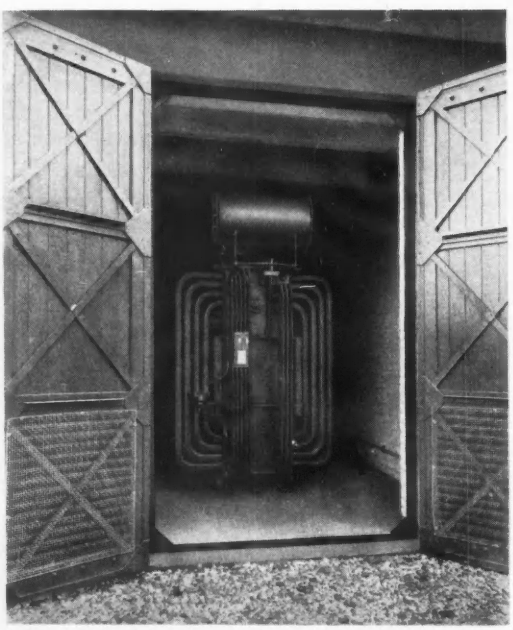


Fig. 5.—2,750 kVA transformer, 20,000/5,500 volts in the substation of the North Eastern Electric Supply Co. Ltd.

ELECTRIC DRIVE OF MILLS.

Piercer Mill.

The piercer mill, fig. 9, handles billets up to 7 inches in diameter, the roll diameter being 17 inches,

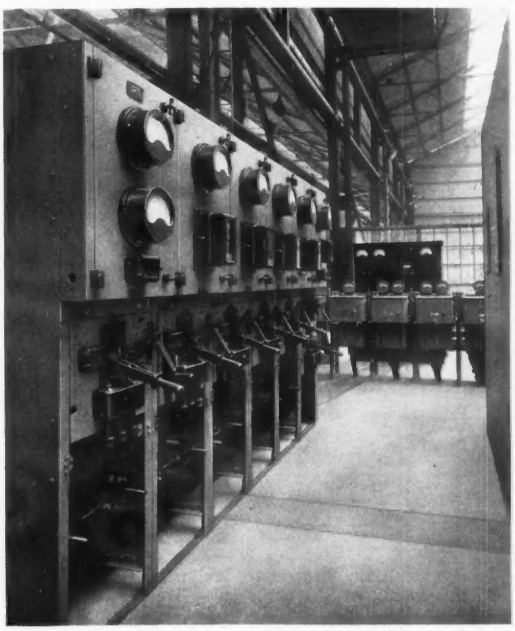


Fig. 6.—5,500 volts S.V.D. type switchboard with part of the pedestal oil-immersed industrial switchboard and the Ward-Leonard motor generator set control cubicles in the background.

and roll width 23½ inches. It is driven by a slipring induction motor with a continuous rating of 720 h.p., which runs direct on the 5,500 volt circuit at a speed of 960 r.p.m. The drive is through gears which give a roll speed of 70 r.p.m. and the motor is controlled by means of a liquid starter.

Pilger Mill.

The Pilger Mill is a two-stand mill, the stands being arranged in parallel. They are driven from a common shaft by the direct current Ward-Leonard controlled motor, which has a normal rating of 540 h.p., but with an overload capacity enabling it to give 2½ times normal output 120 times per minute. Its speed variation is from 600 to 1,200 r.p.m., and the drive is through a 4 : 1 reducing gear. The high speed gear shaft is equipped with two flywheels 4 feet in diameter and 10 inches wide.

The detail of the control of the motor is given in fig. 10. In general, the methods employed are in accordance with standard Ward-Leonard principles

and need not, therefore, be described in detail. But reference should be made to the method of operation and certain safeguards which have been added.

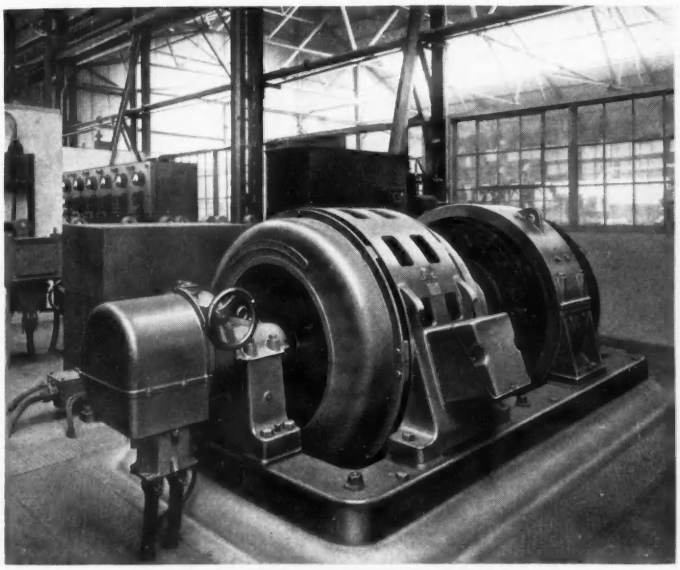


Fig. 7.—The main electrical control room with the Ward-Leonard motor generator set supplying the Pilger mill motor in the foreground.

The mill is operated from a desk control panel, fig. 2, which is equipped with start, stop, inching, forward and reverse push buttons, also speed regulator, speed indicator and ammeter, with scales for both current and horse-power. A recording wattmeter is provided on the Ward-Leonard control panel, and this affords a clear indication of the power taken for rolling each billet.

Before starting up the motor it is of the utmost importance that the auxiliary fan motor, oil and water pump motors and grease pump motors should be in operation. They are therefore arranged for starting by direct-to-line starters, modified for sequence interlocking. The driving motor cannot be started except for inching, until these auxiliary motors are running and should any of them fail the main motor is tripped out.

The general arrangement of the Pilger mill with its driving motor, control panel, auxiliary motors, etc., is seen in figs. 11 and 2. The diameter of the Pilger roll body can be adjusted from 8 to 12 inches by the 10 h.p. motor seen in fig. 11. The "pass" in the rolls through which the billets travel is of a varying profile, divided into three zones. The first is a "clearance" zone where the feed of the billet is made, the second is the working zone which forges down the hollow billet to correct thickness, and the third zone is the finishing "pass," which directly sizes the outside diameter of the finished hot tube. These three zones operate consecutively, and instead of a normal easy rolling procedure, a definite forging action takes place which is of positive benefit to the steel itself, and produces a hot rolled tube of the very finest quality.

The feeding apparatus of the mill and the lifting tables are hydraulically operated.

Run-outs on the rear of the Pilger mill are equipped with kick-off devices which permit the tubes to be thrown upon an electric roller conveyor between the two run-outs. When on the conveyor the tube ends are cut off by means of two hot saws driven by 20 h.p. squirrel cage motors running at a speed of 1,450 r.p.m.

Reducing Mill.

The reducing mill has 8 stands with rolls of 12 inches diameter. Tubes enter at a speed of about 2 feet 6 inches per second, the actual speed depending on the diameter of the tube. The driving motor, which is a pipe-ventilated slipring machine, is rated at 135 h.p., 720 r.p.m. Its control is by means of an oil-immersed stator switch and an oil-immersed rotor switch of standard construction, and in addition an air break changeover switch is provided in the stator circuit to allow reversal in the event of tubes buckling.

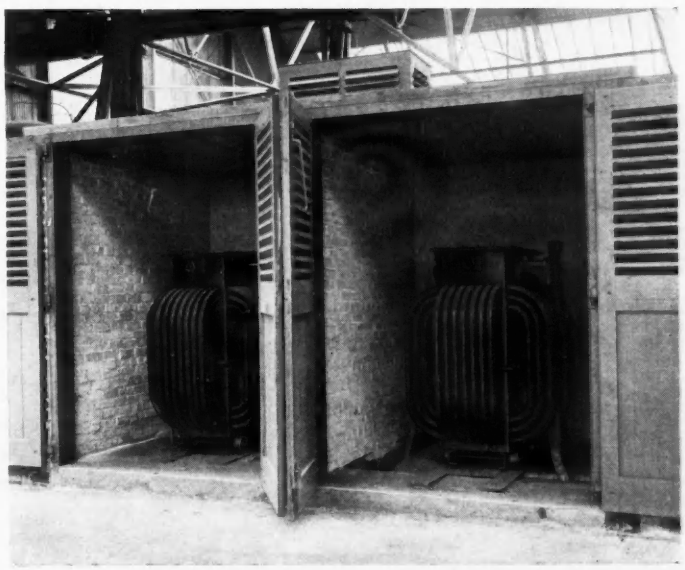


Fig. 8.—The two 450 kVA 5,500/440 volt G.E.C. transformers supplying auxiliary motors and lighting circuits.

AUXILIARY MOTOR DRIVES.

The auxiliary motors drive a wide variety of apparatus, including draw benches, cooling banks, reeling machines, straightening machines, hot and cold saws, air compressors, three-throw ram pump, furnace pusher arm, centring machines, etc. In many cases the drives call for no comment, as motors and motor control gear are of standard pattern; but other of the drives involve special methods and typical examples of these will be briefly described.

The motors are of either the protected or cowl-cooled type, and many of the starters and controllers are designed for heavy duty.

It is of importance to record that every motor in the installation is provided with an isolating switch adjacent to the motor.

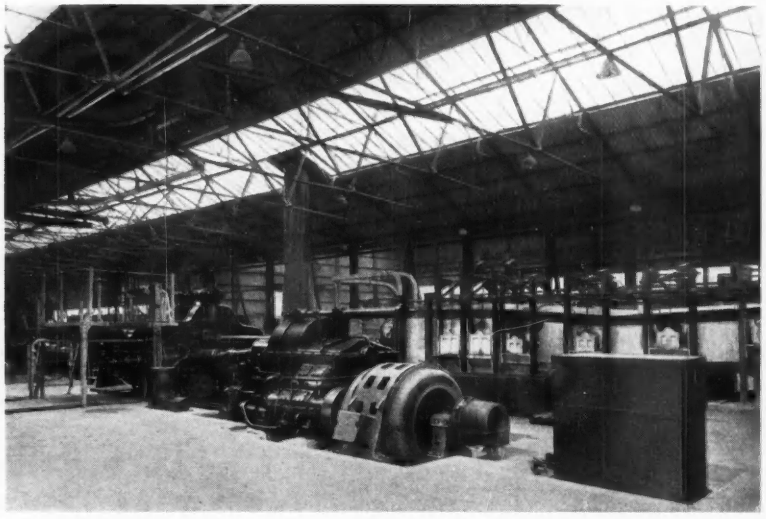


Fig. 9.—720 h.p. 960 r.p.m. slipring motor with liquid starter, driving piercer mill.

Pusher Arm for Reheating Furnace.

The pusher arm for the reheating furnace which serves the reducing mill is driven by a 20 h.p., 960 r.p.m. slipring motor, fig. 13, fitted with a solenoid brake and two limit switches. An interlocking switch is provided at the far end of the furnace in order to prevent the pusher arm being started when the reducing mill is not running; it also ensures that the tube is pushed out squarely. A standard contactor panel is employed, actuated from a steelworks type of master controller which is situated so that the operator can look into the furnace during the running period. The limit switches at the front and back of the arm prevent overtravel and the breaking of water cooling connections.

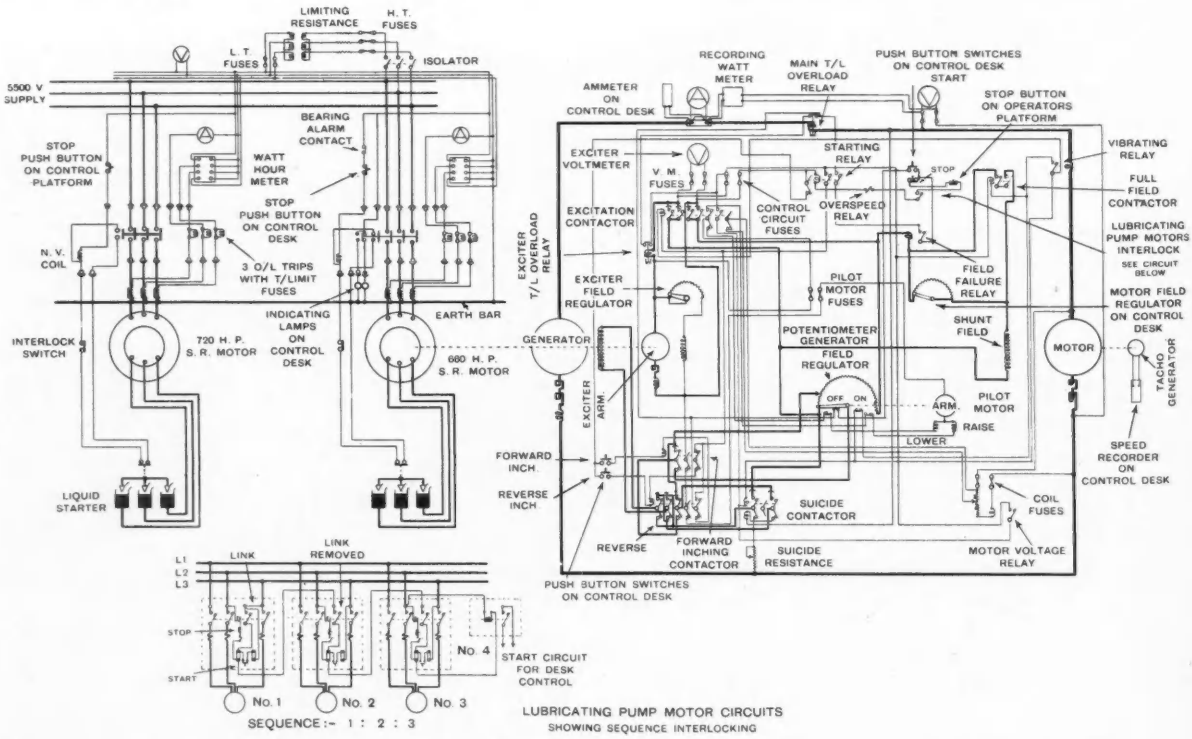


Fig. 10.—Schematic diagram of connections for control of 540 h.p. direct current Pilger mill motor.

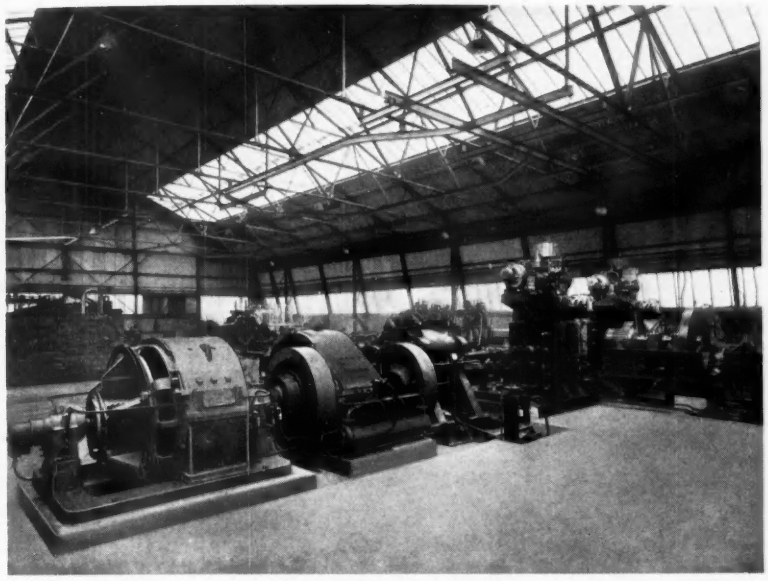


Fig. 11.—540 h.p. Ward-Leonard controlled direct current motor driving Pilger mill, also adjusting and fine-adjusting motors.

Hot Straightening Machine.

The hot straightening machine, fig. 4, is of the cross roll type with two rolls each 11 inches in diameter and 40 inches long. The roll inclination is 11 degrees. Each roll is driven by a 20 h.p. slipring motor controlled by means of a push-button operated stator-contactor circuit breaker and an air-break rotor starter regulator. The pinch roll motor, a 10 h.p. squirrel cage machine, is also shown in fig. 4. It is star/delta started, and is left running continuously during operations, a remote-operated solenoid closing the rollers.

Cold-Draw Benches.

There are four mandrel drawing benches situated adjacent to the cooling beds. The method of driving these benches, rated respectively at 60, 40, 30 and 20 tons, is identical, though naturally there is appropriate variation in the size of the driving motors. Each bench is fitted with a main motor of the slipring type, and a pilot motor, which is squirrel cage. The pilot motor is used only for starting. It enables a slow start to be made, so that a check can be taken to ensure that everything is in order before the main motor takes over the drive. The squirrel cage motor is controlled by a push-button operated direct-to-line contactor starter, and the slipring machine by a contactor-type rotor starter, also push-button operated, and arranged for constant time acceleration. Both starting equipments are mounted in the cubicle on the right of fig. 14. As soon as the slipring motor is started, the squirrel cage machine is stopped automatically. The main motors for driving the benches are 65 h.p., 50 h.p., 40 h.p. and 30 h.p. units respectively for the 60, 40, 30 and 20-ton benches, while the pilot motors have corresponding capacities of 18, 15, 12 and 10 h.p.

Each of the three 20-ton plug drawing benches, which are situated at the top of the bay, is driven by a 45 h.p., 720 r.p.m. slipring motor controlled by an enclosed contactor panel consisting of a combined rotor and stator starter, remote push-button operated. This electrical equipment is shown in fig. 15.

Bright Annealing Furnace.

The continuous bright annealing furnace, shown in fig. 12, presents so many outstanding features that it could not be described adequately in this article; it is hoped to deal with it fully on another occasion. It is believed to be the first time that a furnace of this type has been used in the tube industry in Great Britain, and the results are awaited with great interest. It is anticipated with confidence that an anneal will be obtained whose finish, quality, uniformity and precision will challenge comparison with that achieved by any other method known.

The furnace is 171 feet long overall, and is

Fig. 12.—The continuous bright annealing furnace designed to handle tubes up to 3 in. in diameter and 20 ft. in length. The operating temperature of 1,472° F. is automatically controlled.

designed to handle tubes up to 3 inches in diameter and 20 feet in length; the normal output is 16/17 cwts. per hour, and the electrical loading is 220 kW. The normal operating temperature is approximately 800°C. (1,472°F.), and this is automatically controlled. The electrical supply is taken through a 220 kVA, 5,500/150 volt transformer.

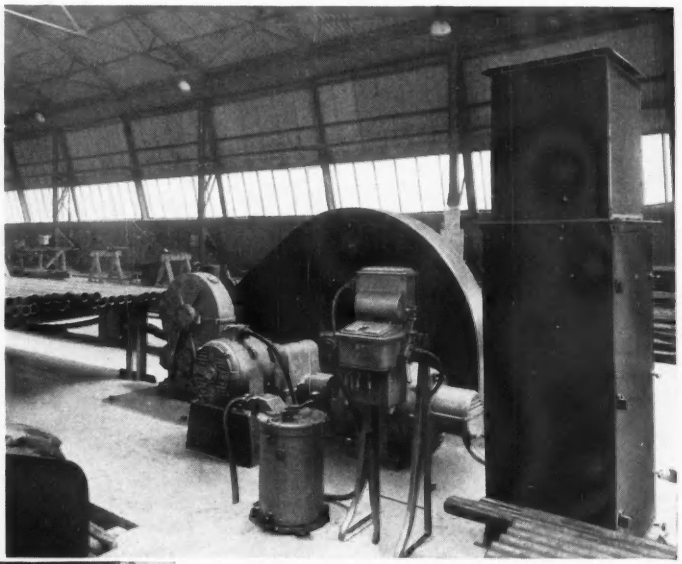


Fig. 14.—Motors for 50 ton draw-bench. The squirrel cage pilot motor is seen in the centre, the main driving slipring motor being partly hidden by the control gear for a reeling machine motor, indicated on the extreme left.

LIGHTING.

Lighting in the main bay is from seventy-nine 400-watt Osira mercury vapour lamps, arranged in dispersive reflectors in two overhead lines and a line of angle reflectors at each side below the crane rails. In the side bay a further fifteen 400-watt Osira lamps are employed. The illumination provided is of a high order in comparison with that normally encountered in similar works, the average intensity being about 9.5 foot candles. Nevertheless, the total works lighting load is only some 40 kW, whereas if tungsten filament lamps had been employed, about 100 kW would have been required for equal illumination.

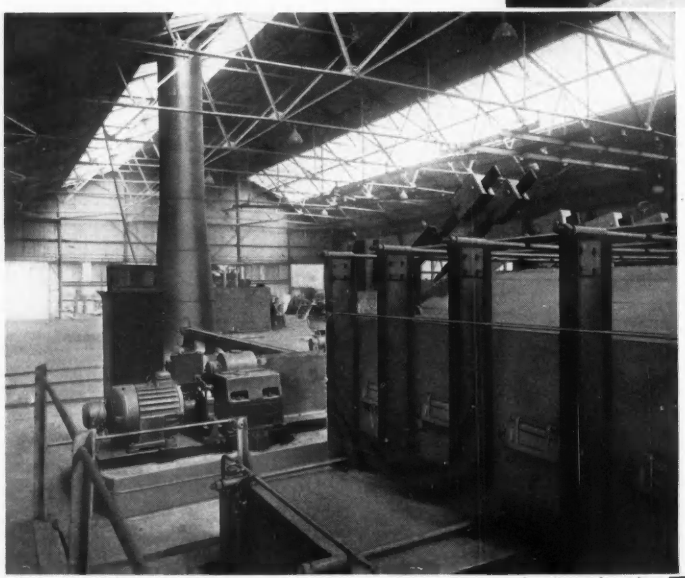


Fig. 13 (Above).—20 h.p. cowl-cooled slipring motor driving pusher arm of reheating furnace.

Fig. 15 (Right).—Three 45 h.p. 720 r.p.m. slipring motors driving plug drawing benches. Combined rotor and stator contactor switch cubicles are seen against the wall.

CABLES AND AUXILIARY DISTRIBUTION.

All the high tension cables are paper-insulated, lead-covered, single-wire armoured, and the low tension cables for power and lighting are either of the same type or V.I.R. lead-covered, single-wire armoured. The cables are laid in ducts which run the full length of the building with cross-overs at suitable spacings. To facilitate this method of cabling, distribution points have been arranged on both sides of the bays giving ample protection and ensuring that extensions to plant will be possible without lengthy cable runs.

* * * * *

In conclusion, acknowledgment should be made of the invaluable work of Mr. Benjamin Price, Consulting Engineer, who was responsible for the general design and layout of the equipment.

High-Power Valves: Construction, Testing, and Operation.

PART II.

By J. BELL, B.Sc., J. W. DAVIES, and B. S. GOSSLING, M.A.

Research and Engineering Staffs of the M.O. Valve Co., Ltd., at the Works, Hammersmith, and G.E.C. Research Laboratories, Wembley

This is the second part of an article (Part I. appeared in the August issue of the G.E.C. "Journal") which was originally presented as a paper before the Institution of Electrical Engineers in March, 1938, and subsequently published in the Proceedings of the Institution.

SPACE-CURRENT CHARACTERISTICS IN THE OPERATING REGION.

(a) General.

THE published characteristic curves for each type of valve are used for the purpose of choosing which type is best suited for a particular use. They are not apparently often used for predetermining refined details of performance such, for instance, as the percentage of modulation harmonics. Such predeterminations would require extreme precision in all parts of the curves, exact knowledge of circuit constants and a good deal of labour in computation; in consequence, experimental study of optimum operating conditions is generally preferred.

Since valves which are expected to give a good life are operated with the filament temperature as low as possible, it is to be expected that there will be an approach to saturation in the part of the operating cycle where the space-current is largest. Now it is just where the space-current is largest that the valve is doing most of its work. Hence, it is particularly necessary that what happens in the region of the onset of saturation should be known, and together with this the effects of changes in the level of saturated emission.

To get characteristics directly by static readings is frequently just possible without undue risk to the valve, but high-power plant is needed. Further, static characteristics are liable to be misleading whenever the space-current is a sufficiently large fraction of the filament heating-current to influence appreciably the emission level—through ohmic overheating of the ends of the filament and "emission cooling" there and elsewhere.

Dynamic methods using peak-recorders or cathode-ray oscillographs are safer for the valve, but are liable to require even more plant. So a good many years ago, before cathode-ray oscillographs such as we have now were available, a simple method was devised by which space-current characteristics could be extrapolated from low-power readings, and this still seems to be adequate.

Simple extrapolation by extending the observed lower parts of curves using the 3/2 power law is not of much use. The onset of saturation is too gradual, more so than may be generally appreciated.

The index of the power-law curve, as shown in the slope of a doubly logarithmic plot, fig. 10, begins to decrease at not much more than one-half of the saturated current, and to reach anything like saturation the voltage has to be raised to nearly twice its value at this point of departure. This early departure is probably valuable in practice, for it about doubles the length of the straight part of the characteristic; for present purposes, however, it is a complication. These effects are common to all types of valve, and seem largely independent of the geometry of their construction. The following analysis of the case of a geometrically simple valve can therefore be taken as being of general application.

This is the low-impedance rectifier type C.A.R.2, which has the "binocular" construction in which

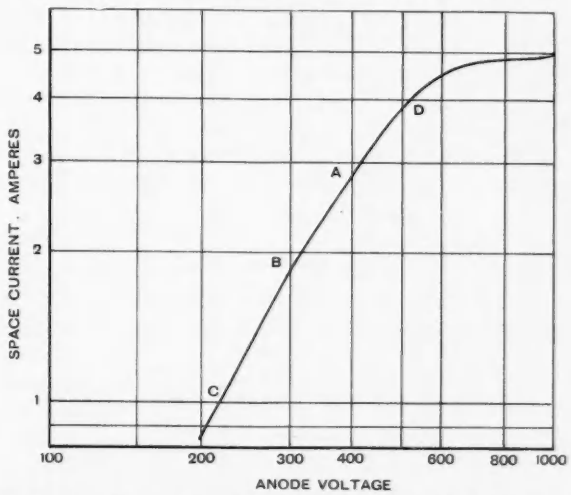


Fig. 10.—Characteristic (plotted to log. scales) of symmetrical diode (type C.A.R.2).

A. Departure from 3/2 power law.
BC. Incipient magnetron cut-off.
CD. Range of linear characteristic.

the filament consists of two straight limbs, each lying along the axis of a substantially complete cylindrical anode.[2 17] A doubly logarithmic plot of a characteristic of one of these valves is shown in fig. 10.

Now in this kind of valve the symmetry of construction, the length (220 mm.) of the filament limbs, compared with their diameter (1 mm.), and the voltage-range of the characteristic, preclude explanation of this slow saturation to more than a very minor extent by most of the usual means, such as asymmetry of the collecting electrodes, screening of one part of the filament by another, and variation of potential, 20 volts (A.C.), along the filament itself. Some other reason or reasons have therefore to be found, and since the effect is but little greater in less-symmetrical valves as long as

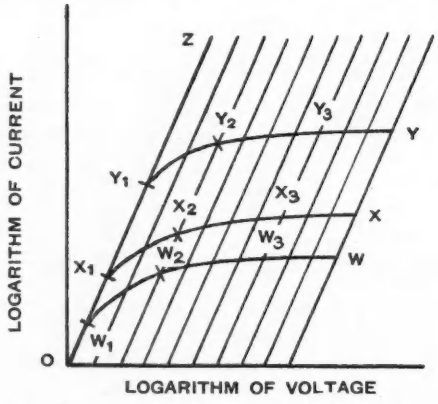


Fig. 11.—Diagram (plotted with logarithmic scales) illustrating extrapolation of space-current characteristic from lower to higher levels of emission.

their filaments are straight, the reasons must be sought in the filament itself.

The most likely reason, physically, for the first departure is that there are local variations in the saturation value in different regions of the filament surface, and a calculation of the distribution of emission along the filament due to the end cooling, is found to account satisfactorily for the departure up to about 90 per cent of the saturation value, that is to say as far as anyone is likely to be practically interested in the characteristic. The calculation followed the methods of Forsythe and Worthing[8] and was verified qualitatively from the distribution of evaporation wastage in a long-life filament (see fig. 17).

The method of extrapolation, to be described below, allows for any local variations in the saturated emission, whatever their cause.

It is, however, of interest to know the reason for the form of the uppermost part of the characteristic since this might have some effect on the extrapolation. The explanation, according to some work by G. W. Warren, shortly to be published, is that we have here a kind of "telescoping" of the Schottky effect[9 10] that is, the increase of the emission above the normal saturation value owing to a finite and increasing field at the cathode surface. That so large an increase as 10 per cent in the emission can be produced by the observed increase of collector voltage, arises briefly from the facts that as long as there is a fully developed space-charge there is no field at the cathode surface, and that as soon as the space-charge is reduced by the increasing initial acceleration of the emitted electrons, the full field due to the potential of the anode, or the equivalent equipotential in triodes, etc., is quickly established there. The initial growth of the field, and therefore of the emission, is found to be rapid, hence the "telescoping" mentioned above, and the increase of voltage required to produce what we have been calling saturation, which is really the establishment of the true Schottky rate of increase, agrees very well with what is observed in the C.A.R.2 type of valve, *i.e.*, some 300 volts in fig. 10. The extent of the effect is really very largely a property of the filament itself, and its existence accounts for the outstanding discrepancy in an earlier analysis of a diode characteristic by one of the present authors[11] and takes priority over alternative explanations, *e.g.*, in terms of local variations of the field at the cathode surface.[12]

After this analysis of the onset of saturation, we can now proceed to the method of extrapolation used. This employs a doubly logarithmic plot, logarithm of space-current against logarithm of electrode-voltage, and can be applied either to a diode, or to a triode with grid to cathode, or to a triode with grid bias, negative or positive, varied in constant proportion to the anode voltage, but with positive grid bias it is the space-current leaving the cathode that must be plotted.

If a number of curves for various levels of emission are plotted as in fig. 11, the result at once suggests the method of extrapolation. We shall describe this in the first place as an empirical rule, and later discuss its probable theoretical basis.

The valve is usually connected as a diode, grid and anode together, so that only relatively low voltages and power are needed. One curve, OZ the "unsaturated" characteristic, is taken as high as grid dissipation permits, and at a filament voltage sufficient to ensure that there is no emission saturation, and another, OX, at the highest filament voltage consistent with reaching full saturation without exceeding the permissible grid dissipation. The other curve below OX is not essential, but is here included to illustrate the principle.

If lines parallel to OZ are drawn through points X_1, X_2, X_3, on OX cutting the lower curve OW in points W_1, W_2, W_3, the intercepts W_1X_1, W_2X_2, W_3X_3, are found to be very closely equal.

Hence to obtain a characteristic which saturates

at a predetermined value Y, *e.g.*, the saturation value at "marked volts" we simply extend the lines through X_1, X_2, X_3, parallel to OZ, and mark off Y_1, Y_2, Y_3, so that X_1Y_1, etc., are all equal to XY, *i.e.*, to the difference in emission level. In practice OZ, except for very low currents, is usually very close to a straight line inclined at the 3/2 power angle.

If the valve had been connected as a triode, a curve would have been obtained which again is of the same form as OX, but displaced laterally to the right by a distance equal to $\log \frac{\mu + 1}{\mu[k + (1/\mu)]}$, where k is the factor of constant proportion between grid bias and anode voltage.

To calculate from OY the corresponding triode curves for various anode voltages, we have to replot OY, this time on ordinary paper, multiplying all voltage readings by $(\mu + 1)/\mu$, and then displace the curve so obtained by $-E_a/\mu$ successively in the ordinary way. The effects of changes of emission level, *e.g.*, those due to changes of $+$ 1 volt on the filament, can be illustrated by a trifurcation of one of the curves.

The tail.

The lower parts of the curves towards cut-off are inserted from direct observation, since the dissipations are low. These lower parts do not follow the 3/2 power law, largely because of the superposed magnetron cut-off effect due to the field of the heating current, which may be between 30 and 75 amperes per limb. This effect is so strong that to get good readings near cut-off the filament current has to be held very constant. The displacement

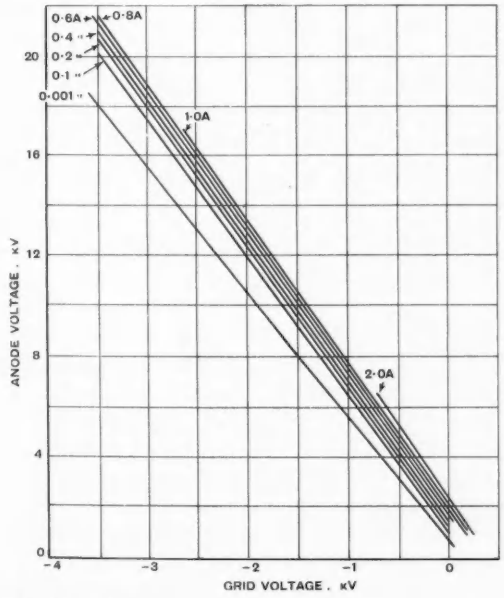


Fig. 12.—Current-contour characteristic of low "μ" valve (type C.A.M.3), showing reduction of "μ" at minute currents only.

rule also may not hold here without modification, owing to progressive reduction of μ, as shown in fig. 12, in which anode voltage is plotted against grid voltage for various anode currents. This form of diagram is convenient for extrapolating the straight lines of anode current to higher voltages than may be available. In types of valve which show

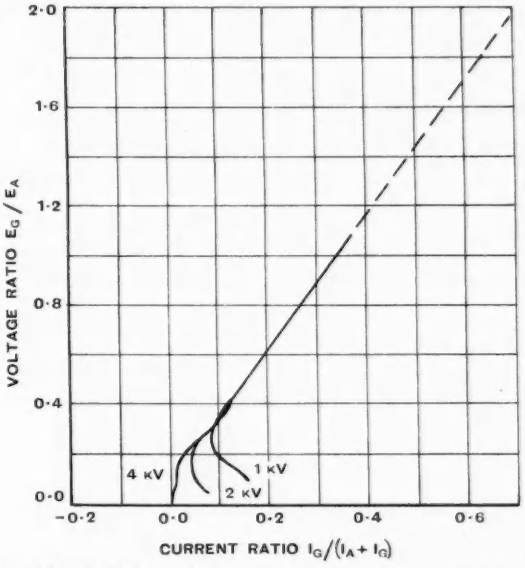


Fig. 13.—Division of space-current between anode and grid.

a marked "tail" at the foot of a high-voltage characteristic, the lower lines on this diagram form a fan. However, in the C.A.M.3 type shown, and in other similar low μ modulator valves, there is very little tail indeed. C.A.M.3 has four straight-filament limbs at the corners of a 10-mm. square within an octagon of grid wires 25 mm. in diagonal. The characteristics are the same whether the filaments lie behind four grid wires, or in the spaces between them. The absence of tail implies a high degree of uniformity of the field round the circumference of the filament in presence of the space charge, *i.e.*, absence of *Inselbildung*.

The addition of a fine spiral to the grid structure to increase the value of μ has little effect on the tail.

Division between anode and grid.

When the grid bias is positive, values of anode current have to be obtained by subtracting the corresponding grid currents from the total space-current. The grid currents are obtained by plotting the ratio of grid current to space-current against the ratio of grid voltage to anode voltage, as in fig. 13. On such a plot we find that outside the region of secondary emission all the plotted points corresponding to various permissible currents and voltages lie on a straight line, and it is assumed that values

of grid current otherwise unattainable can be obtained from this straight line. Theoretically we should use $(E_g/E_a)^{\frac{1}{2}}$ for the plot instead of E_g/E_a since that would be the rule for the simple repulsion of particles from a charged wire. This makes little difference, but E_g/E_a is better, perhaps because of the known development of space-charge round the grid wires. The secondary emission region will be considered later in this section.

Theoretical.

Returning again to the main extrapolation on the doubly logarithmic plot, fig. 11, the theoretical justification of the procedure can be referred to the equations of motion of the electrons, but can be explained as follows :—

At any point of the curved portion of a plot, parts of the filament are emission- or temperature-controlled owing apparently to the end-cooling, and parts voltage, *i.e.*, space-charge, controlled. Suppose

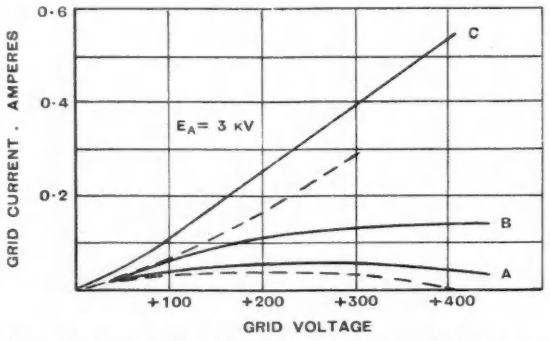


Fig. 14.—Control of the grid-current characteristic by movement of a grid band surrounding the cool ends of the filament.

The broken curves show the limits of valve-to-valve variation before control was applied.

Valve type C.A.T.6.

now that we have a curve, *e.g.*, OX, plotted up to the limit of dissipation of the valve, and we want to draw a curve, such as OY, up to a larger current, say up to n times the current. If we increase any voltage $n^{2/3}$ times, the currents from all the voltage-controlled areas will be increased n times, if the temperature is simultaneously raised by not too small an amount. Again, if we increase the temperature by means of the heating current so that the saturated emission of all parts is increased n times, the temperature-controlled parts will give n times the former current, provided the voltage is increased sufficiently to keep them saturated. If now we do both those things together, *e.g.*, pass from X_2 to Y_2 on the plot, those parts which were temperature-controlled will remain so, and those which were voltage-controlled will also remain so. For, consider a boundary line dividing the two states of the emitting surface. On the one side the necessary excess of voltage, and on the other side the necessary excess of temperature, are still maintained, so that the boundary line does not move. The two areas on either side are thus the same as before, and as the two simultaneous adjustments ensure that the current from each is increased n times, the total current is increased n times.

To sum up, we have arrived at the rule that from any observed characteristic any other can be obtained by increasing the temperature so as to produce an n times increase of saturated emission, and by increasing all controlling voltages $n^{2/3}$ times.

According to the argument, the rule can be applied without our having to know anything of the properties or circumstances of the various local areas of the filament, provided only that we feel justified, *e.g.* by comparing two curves such as OW and OX, in supposing that they do not appreciably interfere with one another. It does not apply in the region of the telescoped Schottky effect.

(b) Grid current characteristics. Secondary emission.

The general form of the lower part of the grid-current characteristics is decided to a large extent by the amount of secondary emission present. The secondary-emission coefficient (number of secondary electrons produced per primary bombarding electron) depends on the bombarding voltage and on the state of the bombarded surface. In general, an electropositive contaminant increases the secondary emission and an electronegative one reduces it. There is comparatively little variation from valve to valve of any type, which indicates that the grid of a high-power valve represents a very clean metal surface and the secondary emission coefficient is approximately that of the pure metal. In the absence of any attempt to reduce the secondary emission, the type of grid current characteristic often obtained is shown in fig. 14 (lower broken curve). This can be dangerous for valves operated in circuits having high grid resistance, as the grid can reach and maintain a high positive potential, with consequent possibility of damage to valve and circuit components. Excessive secondary emission is therefore undesirable, and it becomes necessary to keep the magnitude of the effect under control. This can be accomplished in various ways. For example, the use of tantalum as a grid material results in low secondary emission, and the same result can be achieved by coating a tungsten or molybdenum grid with a substance, such as carbon, having a very low secondary emission coefficient. In fact it has been found that, if the internal surface of the anode is treated with carbon, sufficient finds its way on to the surface of the grid during pumping to produce a marked decrease in the secondary emission co-efficient.

Apart, however, from the grid material, we have found that the secondary emission is not uniform along the length of the grid, but is much greater from the ends, which are opposite the cool ends of the

filament, than from the central active region. Proof of this is obtained from the observation that dimming the filament results in enhanced secondary emission. This behaviour is fundamentally due to the temperature distribution along the length of the filament, and may be explained briefly as follows :—

Owing to the distribution of temperature along the filament, there is considerably more space charge around the grid wires in the central active region than at the ends. This causes the accelerating field tending to remove electrons from the grid to the anode to be stronger at the ends of the grid than in the active region. The ends of the grid therefore contribute a greater number of secondary electrons per unit length than does the active region. Now, if the ends of the grid instead of being an open structure are made in the form of a solid band surrounding the cool ends of the filament system, two things will happen. First, the ends of the grid collect more electrons, and, secondly, the secondary electrons, being produced on the inner surface of the band where the accelerating field of the anode is very weak, cannot escape, so that the effective secondary emission is reduced.

This effect was explored in a C.A.T.6 valve, having a movable grid band at one end of the grid, and the results will be seen in fig. 14. Curve A shows the grid-current characteristic when the band overlaps the filament system by only 2·5 mm., the length of the filament loop being 180 mm. Curve B shows that when the overlap is 12 mm., the effective secondary emission is reduced considerably, and with an overlap of 20·5 mm. (Curve C) the secondary emission is entirely swamped, but here the band covers part of the filament at nearly full temperature and steals anode current. The effect of these changes on the class-B operating characteristic is shown in fig. 15. For type C.A.T.6 a grid-band position corresponding to curve B has been adopted, and other types are treated on their merits.

One of the results of secondary emission is that the number of watts dissipated in the grid cannot, under most operating conditions, be easily calculated. Even under static conditions, the product of grid voltage and grid current only gives the true number of watts if there is no secondary emission. In order to measure the grid watts any instrument which gives a measure of grid temperature may be used, and perhaps the simplest method is the use of a surface thermopile as a radiation indicator. Although the amount of radiation from the grid is usually much smaller than that from the filament the sensitivity of the instrument is sufficient to give an accuracy of, at worst, 5 per cent, which is ample in most practical cases.

Magnetic modification of grid characteristic.

The upper part of the grid characteristic depends mainly on the ratio in which the space-current is divided between grid and anode.

That there is another factor controlling this ratio, additional to the geometrical dispositions, is shown by the difference between C.A.T.14 and C.A.T.12.

In these two types the relative positions of fila-

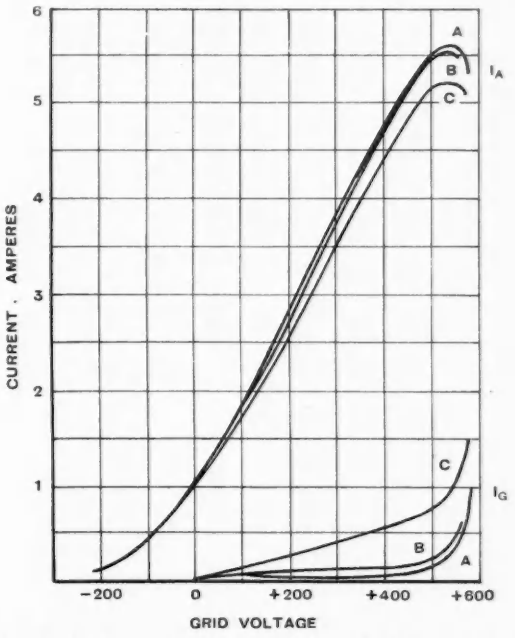


Fig. 15.—Effect on the "class B" operating characteristic of the distance by which the grid band overlaps the cool ends of the filament.

Curve A. Grid band overlap 2.5 mm.
Curve B. Grid band overlap 12 mm.
Curve C. Grid band overlap 20.5 mm.

Valve type C.A.T.6.

ment wire, grid structure, and anode, differ very little, and yet the grid current is proportionately appreciably different in C.A.T.12.

The further factor seems to be the magnetic field of the filament heating-current, which is some 71 amperes per limb in C.A.T.12, and 56 amperes in C.A.T.14. The influence of this does not extend very far out, because in C.A.T.10 with the same 71 amperes filament placed only some 30 per cent further from the grid the current ratio falls to the same value as in C.A.T.14.

This effect has not been studied fundamentally in terms of the motion of the electrons; still there is some further experimental evidence about it. When oscillograms are taken with the filaments heated by 50-cycle alternating-current—though this has been done only with another type, C.A.T.6—the grid current is found to be strongly modulated at 100 and 200 cycles, having two maxima and one minimum in each half-cycle of the heating current.

Hence even with D.C. heating we should be led

to expect different ratios of grid current to anode current if the filament heating-current is different, as it is between C.A.T.12 and C.A.T.14.

This effect must also have some influence on the output modulation, or "hum," produced when amplifier filaments are heated by alternating current. If there is a grid-leak, as in Class "C" anode-modulated, there will be grid modulation. Again, whenever the grid current is comparable with the anode current the latter will be modulated by subtraction of the grid current from the total space-current. Finally, there may be direct modulation of the space-current itself. Where the resultant hum is small, it is possible that one type of modulation may be opposing the others.

In an experimental version of C.A.T.6 which had a three-phase filament system, even "static" oscillograms, *i.e.*, those taken with fixed grid and anode voltage, showed very complicated waveforms, consisting mainly of triple-multiple harmonics —300, 600, etc., cycles. The three-phase arrangement could not be expected to eliminate such harmonics, and it is found that a pair of standard single-phase valves with filaments heated in quadrature by Scott-connected transformers and eliminating both 100- and 300-cycle components gives a much lower level of hum.

FLASH-ARC BREAKDOWNS (ROCKY POINT EFFECT).

The spontaneous breakdown of the vacuum insulation leading to a complete short-circuit of the valve by a vacuum arc, and occurring after a time-lag of anything up to some thousands of hours, was described to this Institution some five years ago.[3] It was felt at that time that, although the initiation of the discharge was not understood, enough was known about its later stages to enable breakdowns in operation to be made so rare as to be negligible.

A residue of doubt whether this would be possible for larger valves was already being dispelled, although it was known that the same degree of protection as for smaller valves could not be obtained on the circuit side.

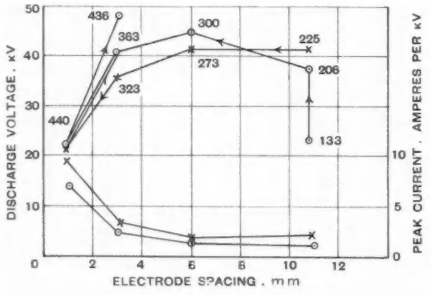


Fig. 16.—Flash-arc (Rocky Point) discharges in experimental tube with variable electrode-spacing.

Upper curves. Discharge voltage.
Lower curves. Peak current in discharge.
Points ⊙. Voltage pulsating at 700 kc.
Points ×. Voltage continuous.

These tentative conclusions have been shown by the experience of later years to have been sound, in that a progressive increase in anode voltage up to 18 or 20 kV for the later types of valves has resulted in little or no trouble in six stations which have been in operation for one or two years, using two different types of valves.

The establishment of this later improvement has resulted mainly from a general increase in the smallest clearance between the grid and anode systems. This increase was adopted in valves intended for the higher voltages, after it had been found by direct comparison that an increase from 9mm. to 25mm. in the C.A.T.6 class of valve raised the permissible overvoltage on a short test by more than 50 per cent above its normal value for the smaller clearance.

Investigation on the lines of the previous study showed that the way in which increase of clearance reduces the chance of breakdown is not altogether simple.

By using a movable anode in the form of a copper disc mounted on a metal "bellows" opposite to a flat-headed loop of 1 mm. tungsten wire as cathode, two things were established.

First, as to the voltage required to produce a discharge with a short time-lag, there was the somewhat surprising result that with the electrodes in anything approaching their final state it was unusual for a reduction in clearance from 12 mm. to 3 mm. to produce any notable fall in the discharge voltage. This is illustrated in the upper pair of curves in fig. 16. Here the surface field in kV per cm. on the side of the cathode loop facing the anode is shown for each discharge point.

The progressive increase of field towards the smaller spacings where a discharge should be easier to establish makes it seem unlikely that breakdown is any simple consequence of the field, high though that is. The results shown by Mason[13] for smaller spacings from 1·2 mm. downwards, agree better with our general experience than his stated conclusions would imply. His later points show a similar rise in field.

Anderson,[14] however, has published results generally similar to ours.

The points appear in pairs because the observations, starting from the largest spacing and returning one step back from the smallest, were taken alternately with a voltage pulsating at 700 kilocycles between zero and the value shown, and with a continuous voltage. The small difference in the run of the two sets of points shows that the time required to build up conditions for a breakdown is very short.

Examination of the currents passing in the discharges—which have not so far been recorded by other investigators—throws some further light on what is happening.

The lower pair of curves show the peak value of the discharge current expressed in amperes per kilovolt. The theoretical value for an undamped discharge of the circuit used, 0·0002 μF and 4·5μH is 7 amperes per kV and the observed peaks fall below this for the larger spacings, so much so that at 6 mm. or over at least nine-tenths of the initial energy of the condenser is used in building up the arc. Even so, in this particular experiment the current readings were higher than usual at the larger spacings.

Evidently the important point is that increase of spacing reduces the chance of a complete breakdown.

Nevertheless, there are other conditions to be satisfied, for if, as in fig. 16, the electrodes were in a state where the general level of discharge voltage was below the maximum, change of spacing made much less difference to the currents, and so little or no advantage from the increased spacing remained.

However, the satisfactory operating experience shows that such conditions do not occur in finished valves.

The view that the presence of residual gas at relatively high pressures has no influence on the breakdown has been supported in operating experience. Considerable numbers of valves have been allowed to soften in operation up to pressures of the order of 5×10^{-4}mm. without any flash-arc breakdowns being reported.

The main principle on the circuit side of not permitting too much discharge energy to be too rapidly and continuously available still stands.

OPERATING CONDITIONS.

About the operating conditions for high-power valves within their stated ratings there is little to be said. The need for constancy of filament supply voltage, if the proper average life is to be attained, is now well understood. For switching on the filaments and applying the anode potential, certain recommendations are made.

In the case of the filaments, the voltage should be applied in increasing steps over a period of about 30 seconds. The process is necessarily slow for two reasons. First, when the filament is cold its resistance is low and the current it would take from a well-regulated supply at full voltage, *e.g.*, a transformer tapping which happens to suit, might be 10 times the working value. The magnetic forces would thus be increased 100 times, and magnetic distortion would be unnecessarily encouraged, apart from possible catastrophic action on the initially brittle filament. Secondly, the temperature can overshoot the working value locally if there is sufficient local increase above the normal resistance per unit length, because of the local concentration of voltage in any region whose temperature, and therefore resistance, is rising more rapidly than elsewhere. The natural instability of the filament in this respect is thus exaggerated, and all filaments being affected more or less alike, the result may be simply that the average life is reduced without the reason being at all obvious. It is therefore recommended that for the first 10 seconds the filament current should not exceed 70 per cent of the working value; for this the applied voltage will have to be only some 7 per cent of the normal. After this, the voltage may be increased fairly rapidly, but so that the current never exceeds 130 per cent of the normal. The final voltage regulation has to be performed some minutes later when the leads, etc., will have reached a steady temperature.

As regards the anode potential, after any interruption during normal operation this may be switched on at a maximum of 70 per cent of the normal, and then after 2 seconds increased in one step to the full value.

For new valves, or valves which have been out of commission for some time, it is recommended that the initial voltage should be 5,000 for 10 minutes. This is followed by a gradual increase to the full value in not less than 20 minutes.

The cooling water must be pure enough to keep the anode free from serious deposits without requiring inconveniently frequent cleaning. For this it is recommended that the total dissolved solids shall not exceed 15 parts per 100,000, nor the solids precipitated on boiling 4 parts per 100,000, nor the conductivity 300 reciprocal megohms per cm. cube. These are limiting values; purer water is better.

LIFE.

The high standard of reliability demanded of transmitting valves to-day has already been referred to. Premature failures are to be avoided, and the failure zone restricted to a reasonable statistical percentage of the average life. A long average life is also desirable. Some idea of the standard achieved may be obtained from the overall average life of all reported failures of all types of cooled-anode valves. This has increased from 4,700 hours in 1932, to 6,400 hours in 1936.

There are many possible causes of failure, but filament burn-out is the only really fundamental cause. It may be delayed but cannot be prevented. The maximum life any valve can have is therefore the life of its filament, and we shall first consider the various factors which affect the life of a filament of pure tungsten, operating at a temperature of about 2,500°K. Filament failure is due to gradual wastage by evaporation, and eventual overheating of the thinnest point. It has been found, by examination

of large numbers of burnt-out filaments, that failure occurs when the diameter is reduced by 10 per cent by evaporation. This rule holds whatever the initial diameter, and was first enunciated at the American General Electric Co.'s laboratories, for lamp filaments of 0·1 mm. diameter or less.[15] The wastage of various filaments of different original diameters between 0·82 and 1·33 mm. is shown in fig. 17. There is a considerable length over which the wastage is uniform, indicating the region of uniform temperature. The ends show practically no wastage; this is due to cooling by the supports, and fig. 17 also shows the cooling effect of the bracers. Evaporation appears to proceed normally until the diameter is reduced by about 10 per cent over a considerable proportion of the length; instability then sets in, and the temperature of a short length increases rapidly. Once started the effect is cumulative, and burn out follows quickly. This point is usually, but not always, the expected hottest point of the filament. The 10 per cent reduction in diameter applies for wire sizes from less than 0·1 mm. to more than 1 mm., and holds throughout the operating range of temperatures.

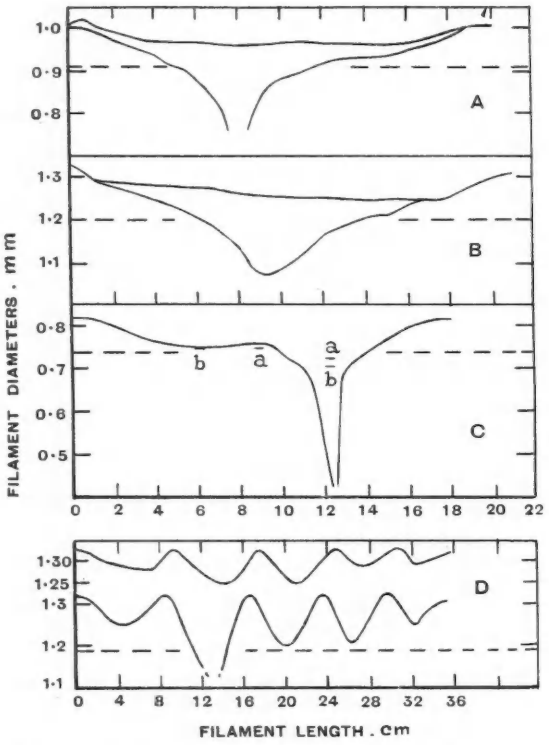


Fig. 17.—Reduction in filament diameter through wastage in operation.

A. Valve type C.A.R.2; 6 335 hours (overburnt about 5%).
Both limbs shown, one only burnt out.
B. Valve type C.A.R.4 (V.T.36); 19 400 hours.
Both limbs shown, one not quite burnt out.
C. Valve type C.A.T.6; 10 817 hours.
One limb of one loop shown in full.
a. Measurements at points on companion limb of this loop.
b. Measurements at points on companion loop, wastages on both limbs equal.
D. Valve type C.A.T.10, early specimen with too many bracers. One of 3 burnt out limbs shown, and one of 3 companion limbs of other polarity.

Broken line shows levels for 10% loss in diameter.

The life of a tungsten filament is therefore directly proportional to its diameter for the same temperature, but as the heating current varies as the 3/2 power of the diameter, economic and other considerations (*e.g.*, end-cooling and magnetron effect) preclude very long lives being obtained simply by using large diameter wires.

Knowing that a filament will burn out when evaporation reduces its diameter to 90 per cent of its original value, we can readily and accurately calculate its life. Early life estimations for cooled-anode valve filaments using tungsten evaporation figures of Jones and Langmuir,[5] gave a theoretical life of about one-half the observed average. More recent simultaneous determinations of the emission and rate of evaporation of tungsten by Reimann, using samples of tungsten from the same source as our filaments, show Jones and Langmuir's figures to be high by a factor of about 2, and the estimated life using Reimann's results is in excellent agreement with the actual lives obtained[5 16].

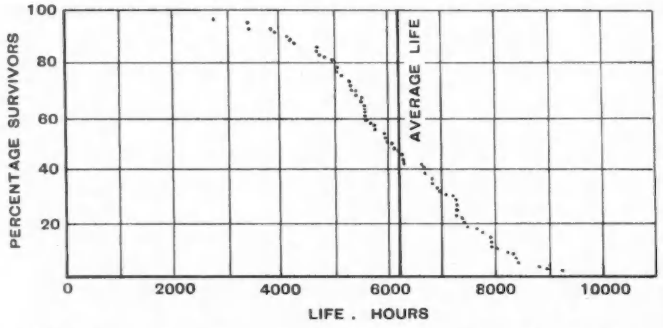


Fig. 18.—Survivor curve for 74 valves, type C.A.T.6, operated at "marked volts" in B.B.C. transmitters.

Failures for filament burn-out only.

Filament voltage schedules

←— MV —→←MV + 1·25%→←—MV + 3%—→MV + 5% — Points ●

←— MV —→←MV + 2%→←MV + 4% — Points ⊙

Glass valves in general give lives of about one-half the theoretical. This is probably the result of a variety of causes, the most important of which is sputtering of the filament due to the fact that the vacuum in glass valves is less perfect than in water-cooled valves. Another contributory factor is the operation of batches of glass valves at a common filament voltage, the exact voltage being decided by the worst emitter, as distinct from the individual adjustment to marked volts for cooled-anode valves.

As already described, it is the general practice to operate the filaments of cooled-anode valves at a temperature just sufficiently high to satisfy the emission demands of the circuit. Filaments are therefore rated on an emission basis, individual valves being stamped

with the filament voltage required to produce a certain emission (marked voltage). A 5 per cent increase in this voltage increases the emission by 50 per cent, but reduces the life to one-half. This rapid variation of life with filament temperature necessitates the use of sub-standard instruments for the adjustment of filament voltage if the maximum life is to be obtained.

Fig. 18 shows a survivor curve for 74 C.A.T.6 valves operated at marked volts in B.B.C. Regional transmitters. This curve is for filament burn-out failures only, and is typical of cooled-anode valves operated at marked volts. Some 60 per cent of the failures occur within $\pm$ 20 per cent of the average life, a few per cent of the valves fail at half the average life, and a few per cent survive to almost twice the average. The average life agrees very closely with the calculated value.

It may be asked whether multiple-filament valves last as long as the equivalent number of smaller valves. The answer is that apparently they do. This would only be so if the behaviour of all the limbs were very nearly equal. For although the parallel connection of unequal limbs must have some stabilizing effect in that initially thicker limbs will run hotter until the consequent more rapid evaporation has produced equality of diameter, yet initial equality is necessary since one-half of the limbs is in series with the other half. The limbs of each system are therefore carefully matched for diameter, and also all the wires are drawn with the same smooth compact surface, to equalize their thermal radiation properties. This last point is, as we have seen, of great importance.

It has been found experimentally that for valves operated at constant filament voltage the emission falls gradually during life. This is to be expected, since at constant voltage, apart from any change in surface condition, the temperature falls slightly during life, and of course there is the reduction in emitting area due to wastage. Emission measurements on long-life valves have shown that the drop in emission is rather greater than would be expected from the above considerations. The difference is due to the fact that the filament becomes less brightly polished during life, with a consequent further reduction in temperature and emission. If the surface condition of the filament remained uniform constant emission during life could be approached by putting a resistance equal to one-third that of the active filament in series and maintaining the whole at constant voltage. The resistance of the leads and of the cool ends therefore gives some compensation.

Constant filament-current operation cannot be tolerated, as in that case temperature and emission increase rapidly, and the life is only about one-fifth of the constant-voltage life. Constant emission is the ideal method of operation, and so far this has only been attained by increasing the filament voltage during life according to a predetermined schedule based on the results of emission tests on long-life valves. The survivor curve obtained by such a method of operation is shown in fig. 19, which is for a batch of C.A.T.6 valves operated in the London Regional transmitter. Comparison with fig. 18 will show that the curve is much steeper, *i.e.*, the spread is much reduced, and the extra-long-life valves are eliminated. The extreme sharpness of the shoulder is partly accounted for by the fact that an increment of filament voltage comes just before this point. The smallness of the overall spread is a verification of the accuracy of the original emission test and its extrapolation.

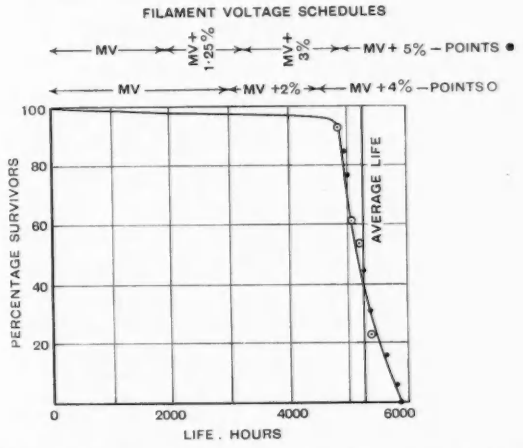


Fig. 19.—Survivor curve for 13 valves, type C.A.T.6, operated under conditions approaching constancy of emisssion during life in the B.B.C. London Regional transmitter.

The filament voltage schedules indicated are approximate.
Failures for filament burn-out only.
MV=Marked volts.

The average life under these conditions is reduced by about 15 per cent, but even so the practice of constant emission operation will tend to grow, since with constant voltage the filament must be overrun originally if it is to have sufficient emission towards the end of its life.

Filament life can be considerably reduced by over-rapid switching, but such failures can be distinguished from normal failures by the nature of the break. Normal failures show a gradual taper on either side of the actual burn-out, while for filaments which have been over-switched the open circuit is more in the nature of a break than a burn-out, and in severe cases the filament may be distorted through the magnetic forces.

The absence of locally-accelerated evaporation in such cases seems to show that the real cause of the instability may be a local increase in resistivity, due to some internal change, rather than an increase in resistance due to reduction in diameter. It is only when the onset of instability is slower, as in the

TABLE 1.

VALVE TYPE, C.A.T.14.

Record of all C.A.T.14 valves used at the Beromünster Transmitter up to 31st December, 1937.

Serial No.	Life, hours	S=Survivor F=Failure	Cause of failure.
13	8 049	S	—
14	4 724	S	—
15	8 014	S	—
16	4 701	S	—

Record of all C.A.T.14 valves used at the B.B.C. Droitwich Transmitter up to 31st December, 1937.

1	7 228	S	—
2	3 127	F	Partly F.B.O.
3	9 483	F	F.B.O.
4	7 660	S	—
5	12 443	F	Leaky bellows*
8	1 421	F	Leak in foot tube*
9	1 896	F	Leaky bellows*
9A	5 162	S	—
10	5 569	S	—
11	8 985	F	F.B.O.
12	1 519	S	—
25	254	F	Leak in anode soldering
26	2 260	S	—
27	1 749	S	—
29	1 864	S	—
46	2 017	S	—
64	1 312	S	—
68	255	S	—
69	211	S	—

Record of all C.A.T.14 valves used at the Motala Transmitter up to 31st December, 1937.

17	10 885	S	—
18	7 249	F	Blue glow
19	4 162	S	—
20	10 004	S	—
21	10 743	S	—
22	1 739	S	—
23	190	S	—

* These valves were manufactured before the trouble with leaky bellows had had time to develop in C.A.T.10 type valves at Warsaw and Rugby.

normal case, that there is time for the usual tapering towards the point of failure to develop. That the cause of instability is not the general loss of diameter according to the 10 per cent rule is also shown by the fact that, if the metal is removed rapidly by sputtering in a poor vacuum, the filament remains stable even when the diameter has been reduced by much more than 10 per cent. However, in valves as we know them the 10 per cent rule is still the expression of a reliable symptom of distress, even though it does not directly represent the actual disease.

The great majority of valves fail through filament burn-out, and only a small percentage through other causes. The effect of other failures on the survivor curve is to flatten the top bend, and hence to reduce the average life. For an established type, the percentage of other failures is very small, and the overall average life approaches the theoretical filament life.

For the largest valves, operation has not yet proceeded far enough to provide data for a survivor curve, but Table 1 shows the complete record of the three stations in which these valves have been in use longest.

TABLE 2.

VALVE TYPES MENTIONED IN THE PAPER.

Type.	Filament. Volts. Nominal	Filament. Amperes. Nominal	Filament. Emission (90% saturated) amperes.	Max. Anode* voltage, d.c.	Max. Anode dissipation, kW	Normal wavelength L=long S=short
High μ Triodes						
VT26	22	41·5	5·5	12 000	10	L
CAT6	18/20	75	10	12 000	12	L
CAT10	30	220	35	15 000	50	L
CAT12	30	220	35	18 000	75	L
CAT14	32·5	460	100	20 000	150	L
CAT17	32·5	460	100	15 000	150	S
CAT19 (E8 30)	31·5	660	150	20 000	150	L
Low μ Triodes						
CAM3	17	70	3/7	12 000	12	L
CAM4	20	75	10	15 000	16	L
CAM5	28	325	22·5	15 000	60	L
CAM6	20	190	14	15 000	30	L
CAT12A	30	220	35	18 000	75	L
Rectifiers						
CAR2	18/20	50	4	15 000	5	
CAR4	18/20	75	7	15 000	6	
CAR6	18,20	120	10/20	20 000	20	

* Subject to certain restrictions as to circuit protection against flash-arcs.

Inspection of the serial numbers of the valves suffices to show that the occurrence at Droitwich of the majority of the failures for causes other than filament burn-outs is due to the fact that that transmitter was the pioneer in the adoption of the C.A.T.14 type.

In conclusion, the authors desire to tender their acknowledgments to Marconi's Wireless Telegraph Co., Ltd., and The General Electric Co., Ltd., on whose behalf the work described was done. They also wish to thank the Post Office, the British Broadcasting Corporation, and other operating authorities, and especially the members of the staffs of the various transmitting stations, whose reports of valve performance, compiled in great detail and at frequent intervals, have been most helpful and encouraging throughout the development of high-power valves.

REFERENCES.

7. J. W. AVERY and C. J. SMITHELLS: *Proceedings of the Physical Society*, 1926, vol. 39, p. 85.
8. A. G. WORTHING: *Journal of the Franklin Institute*, 1922, vol. 194, p. 527; also
   W. E. FORSYTHE and A. G. WORTHING: *Astrophysical Journal*, 1925, vol. 61, p. 146.
9. W. SCHOTTKY: *Physikalische Zeitschrift*, 1914, vol. 15, p. 872.
10. N. A. DE BRUYNE: *Proceedings of the Royal Society*, A, 1928, vol. 120, p. 423.
11. B. S. GOSSLING: *Journal I.E.E.*, 1920, vol. 58, p. 294.
12. B. S. GOSSLING [quoted by A. L. Reimann: "Thermionic Emission," London, 1934, p. 59].
13. R. C. MASON: *Physical Review*, 1937, vol. 52, p. 126.
14. H. W. ANDERSON: *Electrical Engineering*, 1935, vol. 54, p. 1315.
15. S. DUSHMAN: *General Electric Review*, 1915, vol. 18, p. 156.
16. A. L. REIMANN: *Philosophical Magazine*, 1938.
17. A. C. BARTLETT: *Experimental Wireless and Wireless Engineer*, 1927, vol. 4, p. 430.

Signalling at Waverley Station L.N.E.R., Edinburgh.

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Signal Engineer, The Siemens and General Electric Railway Signal Co. Ltd.

Fig. 1.—The approach to Waverley Station from the Mound Tunnel. Two 3-aspect colour light signals with route indicators, warning and shunt signals giving access to the platforms are visible. Waverley West Signal box with its bay window is seen set back into the retaining wall on the right.

AT the Waverley Station of the London & North Eastern Railway at Edinburgh the platforms lie east and west, and trains from London enter from the east end. The signalling at the west end was remodelled and brought into use in October, 1936. The signalling at the east end has since been similarly remodelled under a separate contract and will be put into service in November this year. The whole of the signalling at Waverley Station, and at the junctions next in each direction, is now electrically operated, and two new signal cabins replace seven that were formerly mechanically operated.

Waverley West signal cabin, built into a convenient recess in a retaining wall, gives, from its glass front, a northward view of Princes Street Gardens. Waverley East signal cabin looks upwards to the site of the old Edinburgh gaol which, touched by the wand of progress, is being transmuted into government offices.

The station which stands between these locations dates, in its present form, from 1893. It was the principal station of the old North British Railway and is one of the largest in Great Britain.

Owing to the nearness to the station of the Mound tunnel at one end and the Calton tunnel at the other end the space for transferring engines and trains from platform to platform is very confined, and these movements encroach upon the main approach lines.

As intensive shunting operations of this nature take place at both ends of the station in addition to direct train movements, which, on certain days, reach the number of 500 at the West end alone, it will be evident that the apparatus used in the signalling system must be reliable in operation if for no other reason than to avoid train delays. There are, however, more forcible reasons than that, when it is realised that some of the trains moving under the authorisation of the signals during summer traffic have a length of 1,000ft. and weigh 550 tons and must travel safely as well as expeditiously.

POWER SUPPLY.

The signalling load is 26 kVA (0·85 P.F.) fed from an Edinburgh Corporation mains supply of 230 volts, 50 cycles, 2-phase alternating current. The phases are balanced by being used separately at the east and west ends where the loads are almost equal.

To provide against a failure of the mains supply, an automatically controlled standby plant has been installed, consisting of a 4-cylinder petrol engine developing 38 b.h.p. at 1,500 r.p.m., directly connected to a single-phase alternator through a semi-flexible coupling. The alternator has a double

shaft extension carrying a starter motor and exciter.

The voltage used in the signalling circuits is 110 A.C., except where apparatus is motor operated when 110 D.C. is used. The transmission mains to the remoter parts of the installation carry 440 volts A.C. Suitable transformers are provided, where necessary, to obtain the required voltages, and the direct current is obtained by the use of trickle charged accumulators.

Fig. 2.—View prior to the opening of the new installation showing some of the mechanical signals displaced. The new signal in the foreground has three aspects, red, yellow and green. Below is a route indicator of the stencil type. Below that again is a banner shunt signal. The metal cabinet at the foot of the signal, houses track circuit transformers and condensers.

TRACK CIRCUITS.

The whole of the permanent way within the control of the two new signal cabins, extending to the next cabins in each direction, is track-circuited. This means that the lines are divided as required into insulated sections of track, each of which forms part of a circuiting device to detect the presence of vehicles within its own length. One end of each rail forming part of a track circuit is connected to supply through 110v./110v. transformers with condenser adjustment; the other ends are connected to a two-element vane type A.C. relay at the signal cabin. The presence of a vehicle on the track-circuited section provides, by means of the path from wheel tyre to wheel tyre through the axle, a partial short circuit on the track relay, and causes it to become de-energised.

Track circuits of this kind form the basic protection of train movements and there is a total of 195 such track-circuited sections on the Waverley installations.

These track circuits are utilised in two ways. Firstly, for indication purposes, a large diagram of the permanent way is provided in the signal cabin on which all the track circuit sections are shown. When a section is occupied by a train the corresponding part of the diagram is illuminated. All indication lamps are in duplicate so that the burning out of a lamp will not cause failure to give an indication. The other purpose of the track circuit is to exercise positive control on the operation of points and signals. For example, a vehicle occupying a track circuit will cause to be locked those levers in the signal cabin which operate points fouled by the track circuit, and those which operate certain signals reading over the track-circuited section.

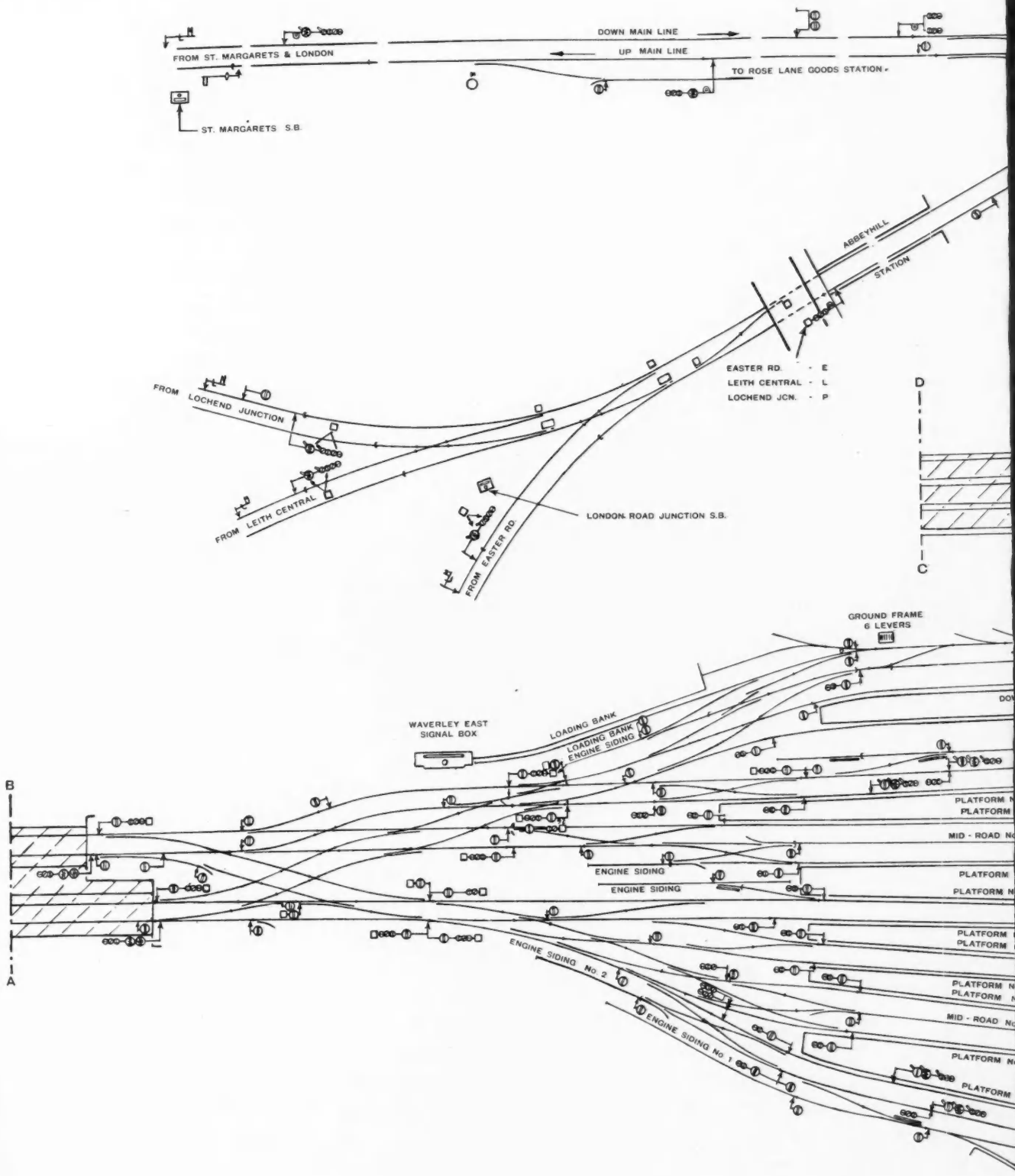
The track circuit is used to prevent a signalman, who has set up a route and cleared a signal for a train, disturbing any points affecting that route until the whole of the train has passed through. It is used to prevent a clear signal being given to a driver when the forward movement is restricted, until the engine has reached a point close to the signal, so ensuring a proper reduction in speed. It is also used to return a signal to the "stop" position as soon as a train has passed and to ensure that a signalman operates the signal lever for each successive train.

POINT OPERATION.

The points are thrown by motor driven machines of which there are altogether 162. Those points which are used for diverging movements are always bolted in position, and the operation of the point machine is to withdraw the bolt, throw the points and rebolt them. The motor works on 110 volts direct current and the whole operation takes about two seconds to complete.

Between the motor shaft and the driving mechanism of the machine is a spring loaded clutch which protects the motor in the event of an obstruction preventing the full movement of the points. The motor current is cutoff in the machine as soon as the point operation is complete and a cam movement allows the motor to over-run slightly until it is dynamically braked. This manner of braking prevents the damage that might occur if the motor ran up to a mechanical stop, as its momentum is considerable.

There are several kinds of protective measures taken to ensure correct response of the points to the movement of the point lever in the signal cabin. To provide against earth faults or line wire contacts a cross-protection relay is included in the point operating circuit—a three-wire control—the function of which is to put the next operative wire to negative


DOWN MAIN LINE
UP MAIN LINE
FROM ST. MARGARETS & LONDON
TO ROSE LANE GOODS STATION
ST. MARGARETS S.B.
ABBEYHILL
STATION
EASTER RD. - E
LEITH CENTRAL - L
LOCHEND JCN. - P
FROM LOCHEND JUNCTION
FROM LEITH CENTRAL
LONDON ROAD JUNCTION S.B.
FROM EASTER RD.
D
C
GROUND FRAME
6 LEVERS
WAVERLEY EAST
SIGNAL BOX
LOADING BANK
LOADING BANK
ENGINE SIDING
ENGINE SIDING
ENGINE SIDING
ENGINE SIDING NO. 2
ENGINE SIDING NO. 1
MID - ROAD
PLATFORM
B
A

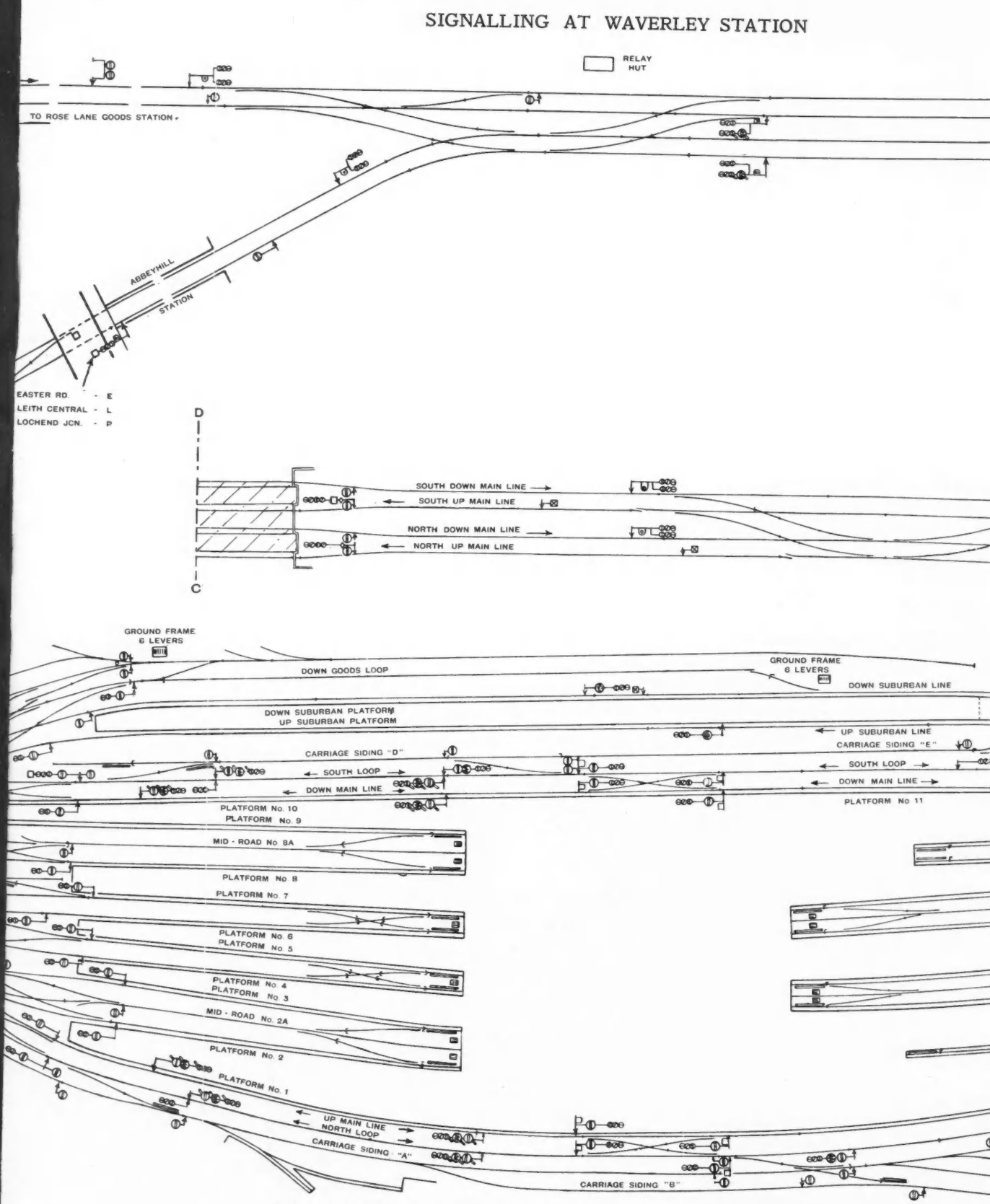
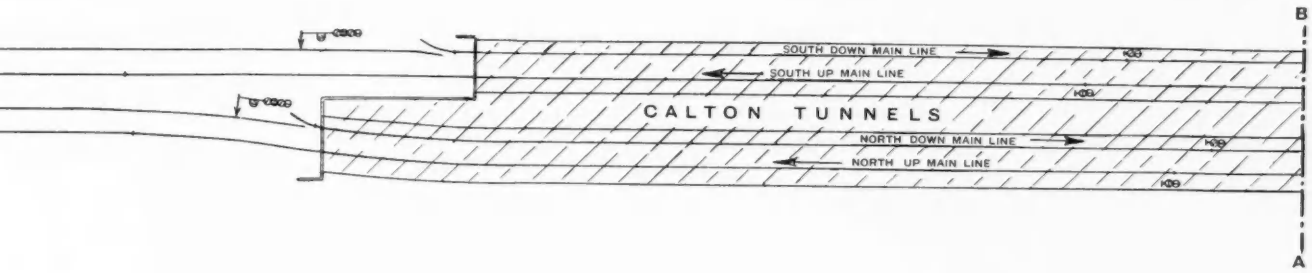
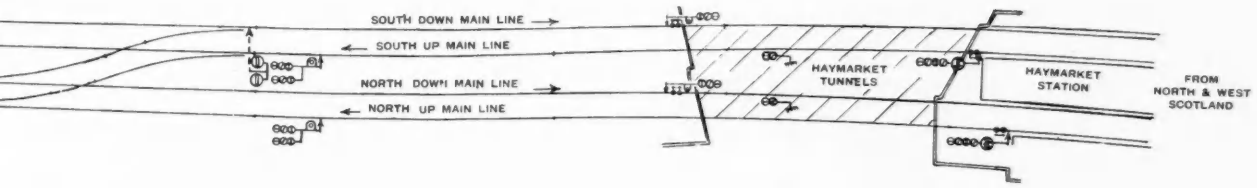
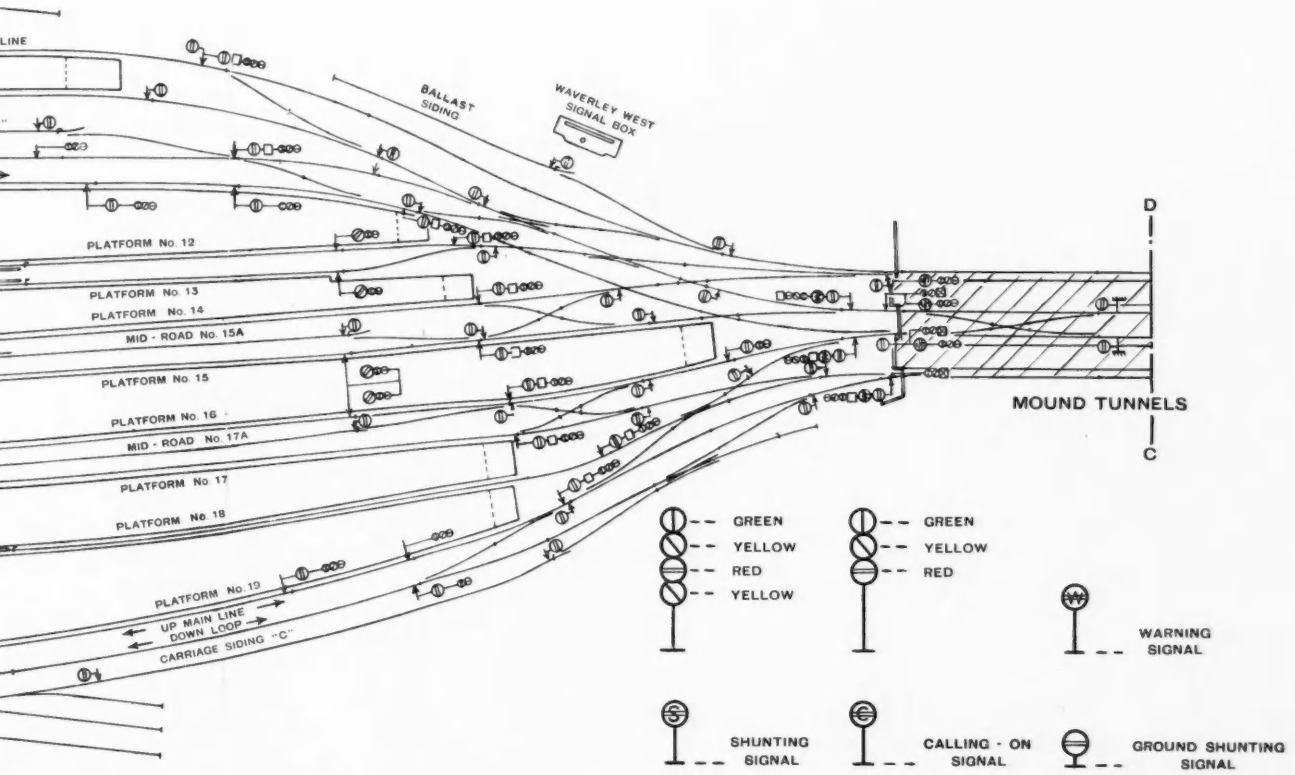


Fig. 3.—Waverley Station, L.N.E.R., Edinburgh, plan showing signalling arrangements.


B
SOUTH DOWN MAIN LINE
SOUTH UP MAIN LINE
CALTON TUNNELS
NORTH DOWN MAIN LINE
NORTH UP MAIN LINE
A


SOUTH DOWN MAIN LINE
SOUTH UP MAIN LINE
NORTH DOWN MAIN LINE
NORTH UP MAIN LINE
HAYMARKET TUNNELS
HAYMARKET STATION
FROM NORTH & WEST SCOTLAND


BALLAST SIDING
WAVERLEY WEST SIGNAL BOX
D
PLATFORM No. 12
PLATFORM No. 13
PLATFORM No. 14
MID - ROAD No. 15A
PLATFORM No. 15
PLATFORM No. 16
MID - ROAD No. 17A
PLATFORM No. 17
PLATFORM No. 18
PLATFORM No. 19
UP MAIN LINE
DOWN LOOP
CARRIAGE SIDING "C"
MOUND TUNNELS
C
GREEN
YELLOW
RED
YELLOW
GREEN
YELLOW
RED
WARNING SIGNAL
SHUNTING SIGNAL
CALLING - ON SIGNAL
GROUND SHUNTING SIGNAL

when the lever and machine are at rest, and so prevent an extraneous operation taking place. Then a system of detection is used for each pair of points. In this arrangement an alternating current 3-position relay is used in conjunction with a specially devised circuit breaker worked by the point switches and the point bolt. If the point tongues do not fit closely to the stock rail; if the bolt of the point lock is not fully home; if the points themselves do not lie for the direction properly associated with the position of the control lever in the cabin the three-position relay will remain de-energised. The other two positions prove the points normal or reversed and the bolt fully home. The contacts of the three-position detection relay are used for indication circuits to show the signalman the state of the points and to control the signals reading over the points.

SIGNALS.

The signals are of two kinds: main line running signals and those used for shunting and such like

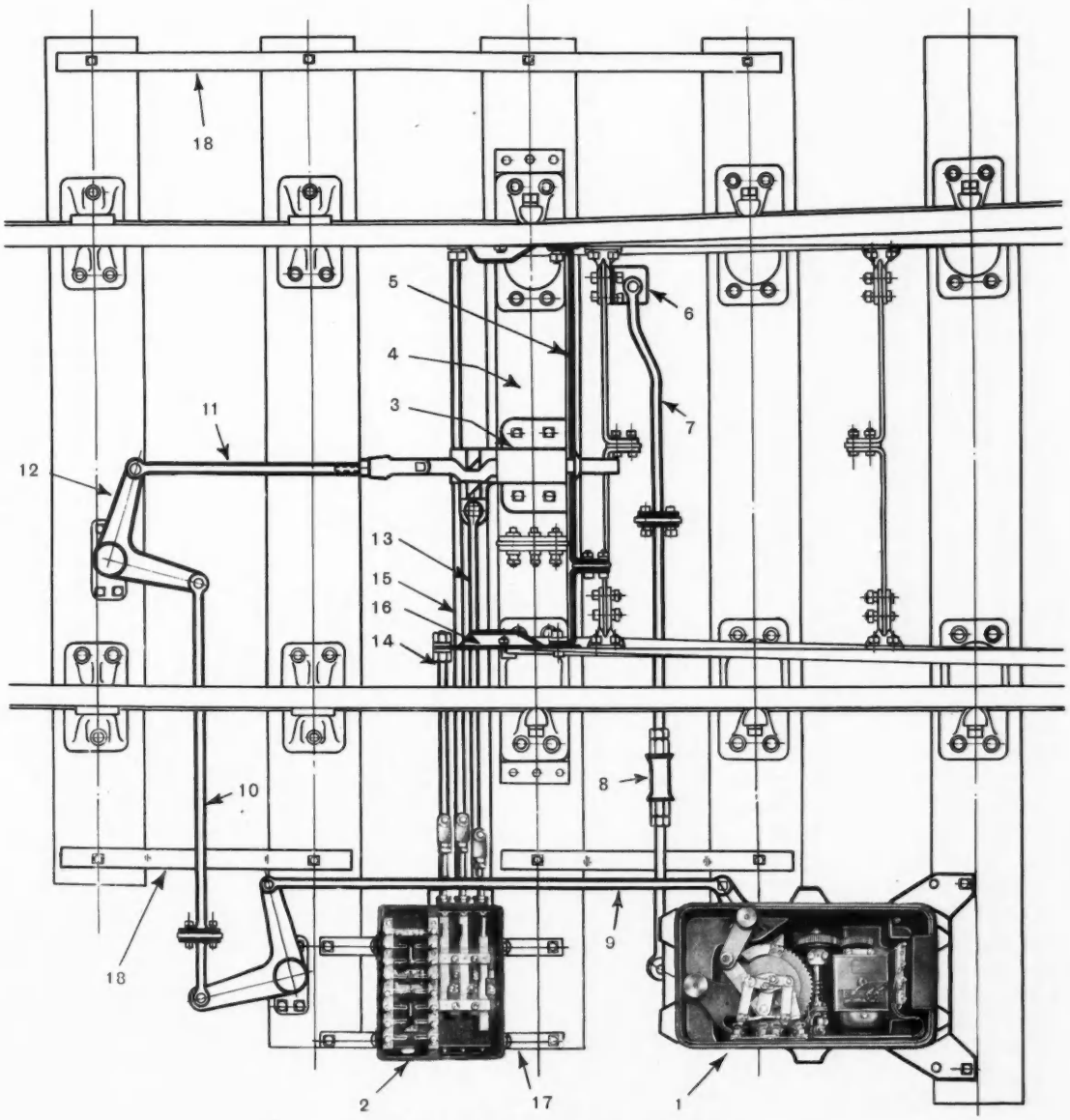


Fig. 4.—Diagram of facing point layout.

No. 1.—The motor operated machine which drives the points by means of connections 6, 7, 8, and bolts the points by means of connections 9, 10, 11 and 12.

No. 2.—The detector for point switches and bolt lock.

No. 3.—The bolt lock.

COLOUR DISPLAYED	MULTI-UNIT SIGNAL 2 ASPECT	3 ASPECT	4 ASPECT	MEANING
RED				STOP
SINGLE YELLOW				PROCEED — PREPARED TO STOP AT NEXT SIGNAL
DOUBLE YELLOW				PROCEED — PASS NEXT SIGNAL AT RESTRICTED SPEED
GREEN				PROCEED

TYPE	SUBSIDIARY SIGNALS NORMAL SIGN	OFF SIGN	MEANING OF OFF INDICATION
GROUND SIGNAL			PROCEED AS FAR AS THE LINE IS CLEAR TOWARDS THE NEXT SIGNAL ONLY
SHUNT AHEAD			PASS STOP SIGNAL FOR SHUNTING PURPOSES
WARNING			PROCEED-LINE CLEAR TO NEXT SIGNAL ONLY—JUNCTION OR LINE IMMEDIATELY AHEAD OCCUPIED
CALL-ON	OR		PROCEED AT CAUTION INTO OCCUPIED PLATFORM PROCEED AT CAUTION INTO OCCUPIED PLATFORM OR SIDING (ROUTE INDICATOR ALWAYS EXHIBITED)

Fig. 5.—Signal aspects and their meanings.

subsidiary purposes. The main signals are the colour-light type, the different colours being displayed through separate optical systems. The signals are composed of 2, 3 or 4 units according to their situation and display as many different aspects as there are units.

These aspects are red for "stop," single yellow for "proceed prepared to stop at the next signal," double yellow for "Attention ! run at medium speed," and green for "proceed." Green is given only if the next signal ahead is showing yellow, double yellow or green. It is given with a single yellow ahead only if there is sufficient braking distance between the next signal and the next but one ahead. If that distance is less than enough for braking, having regard to the speeds prevailing, a double yellow is given.

The signals include individual step-down transformers (110v./12v.) for the signal lamps which, in addition to the main focused filament, have a secondary or standby filament with a higher rating in parallel with it.

Where a signal applies to diverging lines a route indicator is provided in addition to the signal. This indicator displays a number or character which, when the signal is cleared, informs the driver of his route.

The indicator consists of a blind which is mounted on horizontal rollers and has the different numbers or characters painted on it at intervals. The blind is wound upwards or downwards by a 110 volt D.C. motor to display the characters required, the direction and distance being controlled by a selective commutator and electro-magnetic brake.

The subsidiary signals are known as the banner type. Each signal has a display disc of opal glass 15 inches in diameter, illuminated from behind. A red translucent banner in front of this plate is fixed to a spindle passing through the centre of the display glass, and is in the horizontal position for "stop" and inclined at 45° for "proceed." The movement is governed by an A.C. tractive armature magnet. A shunt signal may be located by itself or may be fixed beneath a colour-light signal. In all cases it indicates that the movement permitted is subject to particular restrictions.

INTERLOCKING FRAMES.

On the upper floors of the signal cabins are the

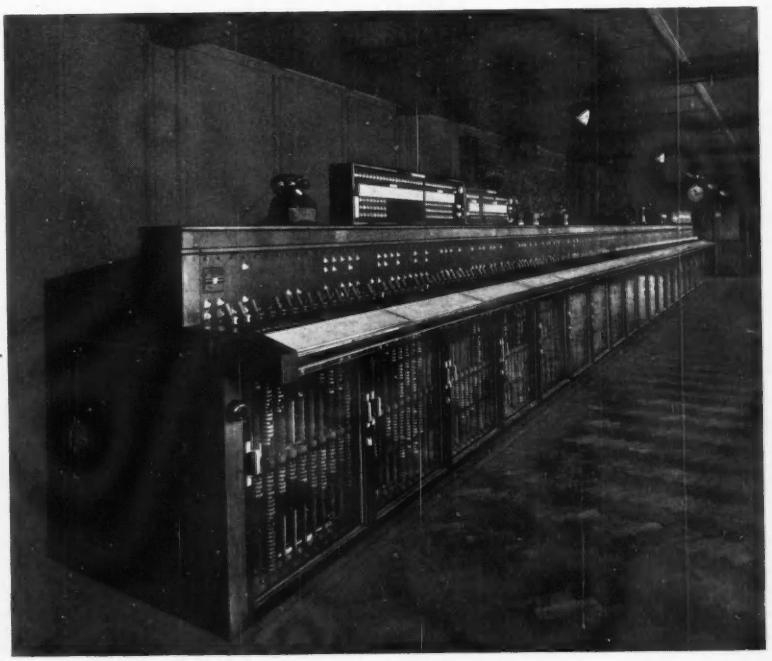


Fig. 6.—Interlocking frame in Waverley West signal box.

levers by means of which the signalman controls the points and signals outside. Each lever is provided with a number of contacts, open or closed according to the position of the lever, and also with two A.C. electro-magnetic locks. These locks are used respectively to ensure :—

(1) That other levers are in a prescribed position before a particular lever is moved, and to ensure they remain in that position.

(2) That points are properly detected and track circuits unoccupied, as required, before signals permit movements of trains.

Behind each point lever an illuminated indicator is provided to show the position in which the points actually lie and also to show whether the lever is free to be operated. Behind the signal levers is given an indication of the aspect showing in the signal, and the character showing on the route indicators.

In Waverley West Cabin there are 227 levers and in the East Cabin there are 207 levers.

TRAIN DESCRIBERS.

In order to deal with traffic efficiently it is necessary that the signalman should be kept informed of the destination and classification of all trains arriving in his area of control, and that he should pass on to the next signal cabin similar information regarding all engines and trains he despatches.

Special instruments, known as train describers, are provided for this purpose, four sets, each consisting of transmitting and receiving instruments, being installed for describing trains between the West Cabin and Haymarket and four sets for describing trains between the East Cabin and London Road and St. Margarets Cabins.

As an example of the number of combinations of description due to the variety of classifications and destinations, it may be noted that the describers for the Up North Line, between Haymarket Central and Waverley West, provide for 19 destinations and 12 classifications, or 228 combinations in all.

A receiver displays up to three descriptions in the order received, three additional descriptions being "stored." When the first description is transferred to an "arrived" column by the arrival of a train, the second and third become first and second respectively and the first in storage becomes the third displayed. If a starting signal is cleared for a train which has not been described to the forward cabin an audible

Fig. 8.—The Relay Room : the relays on the lower shelf on the left are for point detection. Those on the next higher shelf and on the opposite shelf on the right are track circuit relays. Above are signal control relays, etc.

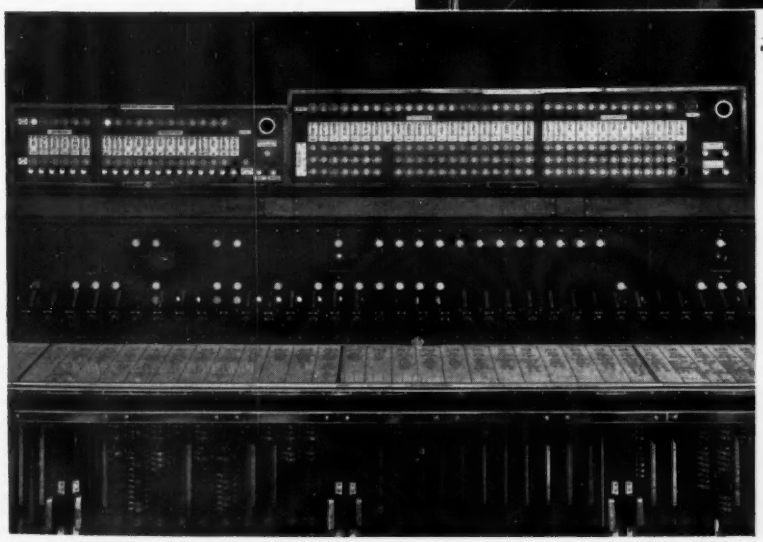


Fig. 7.—Train describers : this detail view of the inter-locking frame shows a transmitter and receiver. The transmitter on the left, is used when despatching trains from Waverley, and the receiver on the right, indicates trains approaching Waverley.

warning is sounded until it is described.

The principle of operation is that of the coded telephone system in which the descriptions transmitted are completely checked back by repetition and proved correct before the indication is displayed.

RELAY ROOM.

On the ground floor of each signal cabin is the relay room. Mention has already been made of track circuit relays and detection relays. In addition there are various relays for signal control which are mounted on steel shelves, and all wiring is run beneath the shelves and brought to the relays through templates that correspond with the relay terminal layout.

In this room, below the relay shelves on the front side, are terminated all wires connected to out-of-doors apparatus. The connecting links or fuses are mounted on porcelain bases screwed to teak battens.

For identification purposes every wire connection in the system is labelled at each end with reference to its function and its point of origin and termination.

CABLE.

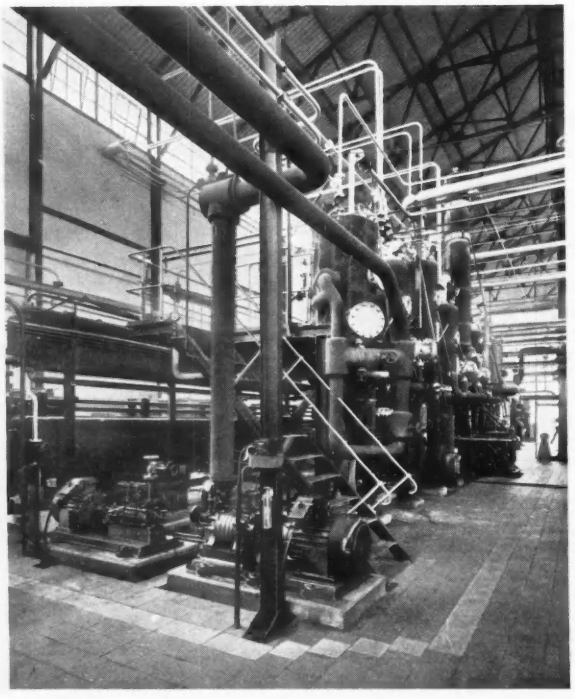
Nearly all wiring has been carried out with rubber-compound insulated, taped, braided and compounded single-core conductors. Out of doors it is run in wooden trunking; indoors it is flameproofed. A comparatively small amount of P.I.L.C. multi-core cable is used.

The amount of wiring involved may be judged by the fact that in the cabins alone nearly 60 miles of wire have been run.

The Siemens and General Electric Railway Signal Company were responsible for the design of all apparatus, circuits and the carrying out of the installation. The point machines, signals, interlocking frame and relays were manufactured at Union Works, Wembley. The Train Describer coding apparatus was produced at the G.E.C. Telephone Works, Coventry, and the motors for point machines and route indicators and the main transformers were supplied by the G.E.C. Works at Witton.

The author has been enabled to give this description of the work through the courtesy of Mr. W. A. Fraser, Engineer L.N.E.R. (Scotland) and Mr. A. Moss, Signal and Telegraph Engineer, under whose immediate supervision the installation was carried out.

Electrical Equipment at an Oil Refinery.



Considerable extensions have recently been made to the oil refining plant of Lobitos Oilfields Ltd., at Ellesmere Port, Cheshire, involving the installation of a large amount of G.E.C. motors and switchgear. The motors in the new treatment section are all of the flameproof type and are remote controlled by push buttons.

The illustration on the left shows the evaporators and stripping columns in the treatment room: in the foreground are two 3 h.p. squirrel cage flameproof motors driving high speed centrifugal pumps at 3000 r.p.m.

Current Limiting Reactors.

By C. H. NUNN, A.M.I.E.E.
Transformer Dept., Witton Engineering Works.

INTRODUCTION.

CURRENT limiting reactors are incorporated in supply networks in order to limit the amount of current which would otherwise flow in the event of a fault. In addition, considerable protection is afforded to the system as a whole by the localisation of high-frequency surges. In this way switches and other apparatus are protected both from mechanical injury and overheating due to heavy short-circuit currents; protective systems can be made more selective, and parallel operation over the system rendered more easy of attainment, since the stability of the system is increased.

In this article it is proposed to discuss the various applications of reactors, the types available, some considerations of design and the more important points to be observed in the choice of installation sites.

Early in the days of electric supply it soon became necessary to install generator, busbar and tie-bar reactors to protect the generators whose voltage at that time did not exceed 11,000 volts.

The concrete type of reactor was evolved for the purpose and proved very satisfactory for some years. About 1920, however, reactors had to be installed in lines with voltages greater than 11,000, and there arose the danger of flashover between turns as well as general insulation difficulties under voltage-surge conditions, especially when the supply was by means of overhead lines.

The solution of the difficulty was to follow transformer practice and use an oil-immersed reactor coil. Again as the power of systems increased, small 6·6 and 11kV feeder reactors were required, and it was generally found more economical to build them of the oil-immersed type.

It is natural that the development of oil-immersed reactors should have been placed in the hands of transformer manufacturers, as the voltage-surge, mechanical stress and coil winding problems are of a very similar nature in both cases. It is thus only to be expected that the construction of reactors should largely follow the lines of established transformer practice.

APPLICATIONS.

Generator Reactors.

The generator reactance usually specified in turbo-alternator stations is of the order of 10% to 15%. If the alternators themselves do not possess this internal reactance, it is necessary to provide additional external reactance in the form of reactors in order to protect the system against a fault either in a generator or feeder.

The connections for generator reactors are shown

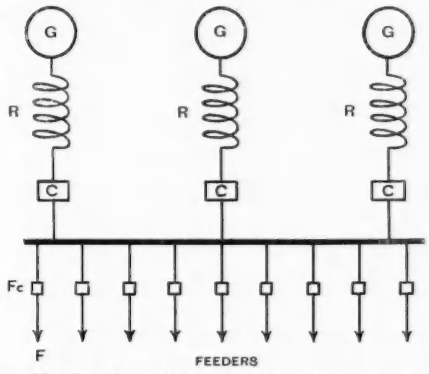


Fig. 1.—Single line diagram showing connection of generator reactors.

in fig. 1, and for convenience only one phase of the system is shown. The generator reactors, R, are connected between the generators, G, and the circuit breakers, C. The feeder circuits, F, with their individual circuit breakers, F_c, are shown connected to the generator busbar.

If an alternator should develop a short-circuit, reactors installed in these positions will enable the remaining alternators to keep in step satisfactorily and will confine the trouble to the faulty alternator. For economy in the size of oil circuit breakers such a scheme is less effective than one incorporating busbar or tie-bar reactors.

BUSBAR REACTORS.

Fig. 2 illustrates the connections of busbar reactors, a scheme which is sometimes required by the general layout of the station, but whenever possible the tie-bar system should be used.

TIE-BAR REACTORS.

The tie-bar method of connecting reactors (fig. 3), is recommended for general use. It possesses the advantage that, under normal running conditions no current is flowing in the reactors, and consequently their use involves no loss of energy.

In this method of connection the station busbars

are divided into a number of separate sections, each with its generator or set of generators, which should be large enough to deal with the normal load of all the feeders on that section. The busbars of the different sections are then paralleled through tie-bar reactors.

In the event of a short-circuit on a feeder, the

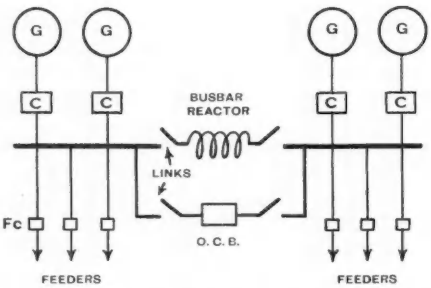


Fig. 2.—Single line diagram showing connection of busbar reactors.

current that can flow into the fault will be limited by a composite reactance the value of which can be calculated from the sum of two reactances in parallel :

(*a*) The reactance of the section generators in parallel supplying the faulty feeder, plus the feeder reactance (if any).

(*b*) The value of the tie-bar reactance on the faulty section, added to the sum of all the other sections in parallel. Each of these sections comprises the reactance of the section alternators in parallel, in series with a tie-bar reactance.

FEEDER REACTORS.

Most system short circuits occur on feeders and it is desirable to localise the trouble to the particular feeder where it originates. This is one of the great advantages of feeder reactors.

With the advent of the Grid and the general increase in the power connected to supply networks, the ratio of the short-circuit current to the normal current of feeders has considerably increased; hence apparatus such as switches, which at one time were quite satisfactory for the duty likely to be imposed on them, tends to become unsuitable under present conditions. Again, for the same reason, it is frequently found that the cable itself has insufficient cross-sectional area to carry the high values of short-circuit current that may occur. For all these reasons feeder reactors are frequently installed to reduce the maximum fault current to a safe value. A group of such reactors is shown in fig. 16.

In the majority of electric supply systems a large number of individual feeders are supplied from one group of generators. If any individual feeder be considered, the curves given in fig. 4 show the short-circuit current in the generator system when a fault occurs on a feeder. The short-circuit current is expressed as a percentage of the normal full load current of the generator system and curves have been plotted for various ratios,

$$\frac{\text{Normal full load generator current}}{\text{Normal full load feeder current}}$$

with various values of reactance installed in the feeder.

The curves are drawn assuming a generator reactance of 10%.

Thus if F = normal full load current in the feeder

G = normal full load current in generator system.

x = value of feeder reactance drop, expressed as a percentage of the normal feeder voltage.

y = value of generator reactance drop, expressed as a percentage of the normal full load generator voltage.

Then :

Total percentage reactance under short circuit condition, referred to feeder capacity $= \mathrm{x} + \frac{F}{G}\mathrm{y}$

Short circuit current in feeder, expressed as a percentage of the normal full load current

$$= \frac{100^2}{\mathrm{x} + \frac{F}{G}\mathrm{y}}$$

Short circuit current in generator system, expressed as a percentage of normal full load generator system current

$$= \frac{100^2 F}{G\left(\mathrm{x} + \frac{F}{G}\mathrm{y}\right)}$$

The curves in fig. 4 show that feeder reactance values of 3 to 5% are suitable for normal requirements.

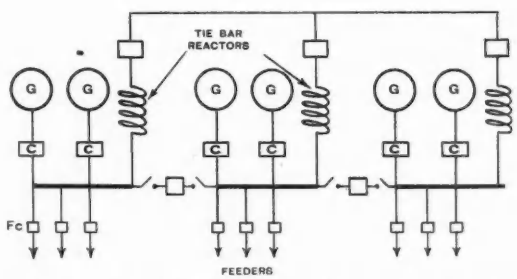


Fig. 3.—Single line diagram showing connection of tie bar reactors.

EFFECT OF REACTOR DURING NORMAL OPERATION.

It is of interest to note that, during normal operation, a reactor has two adverse effects on the

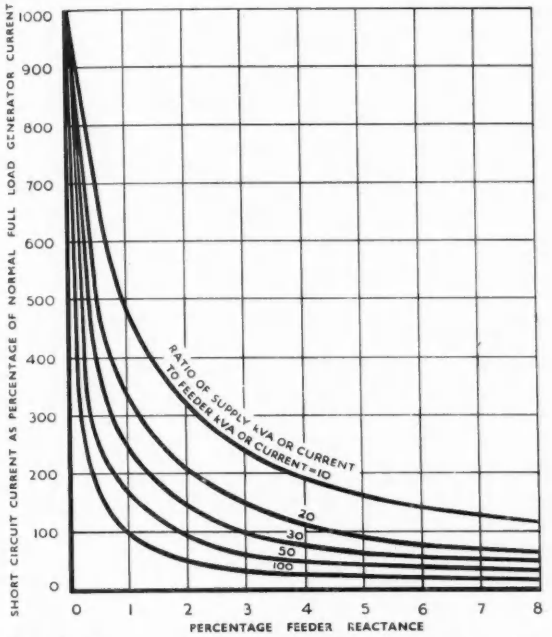


Fig. 4.—Group of curves showing percentage short circuit currents on feeders of given reactance.

system in which it is installed, but from what follows it will be seen that neither is of major importance.

The voltage absorbed by a reactor is proportional to the current which flows through its windings, but being nearly 90 degrees out of phase with that current it has little effect on the circuit voltage during normal service conditions, providing that the power factor of the circuit is reasonably high. This is shown graphically in fig. 5. The tables which follow give numerical examples of the circuit voltage drop at full load with representative reactors.

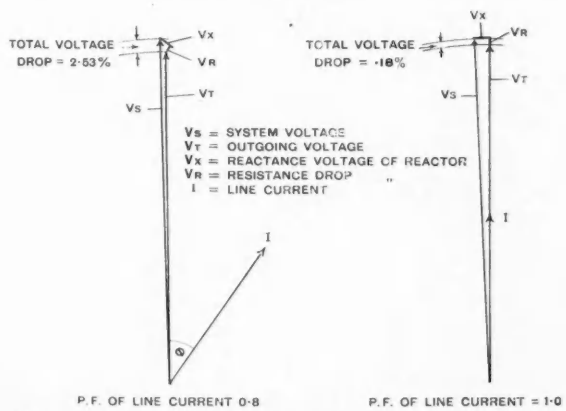


Fig. 5.—Vector diagrams showing effect of reactor drop on circuit voltage at various load power factors, for a 4 % reactor.

4% Reactor. Maximum short-circuit current 25 times full load.

	CIRCUIT POWER FACTOR				
	1.0	.9	.8	.7	.6
Percentage voltage drop of circuit	0.18	1.91	2.53	2.91	3.29

10% Reactor. Maximum short-circuit current 10 times full load.

	CIRCUIT POWER FACTOR				
	1.0	.9	.8	.7	.6
Percentage voltage drop of circuit	0.69	4.97	6.46	7.48	8.29

In order to compensate for the voltage drop during normal operation, the circuit voltage is slightly raised either by adjusting the generator voltage or the tappings of the transformer supplying the circuit.

Again, there is a continuous loss by reason of the energy absorbed in the windings of the reactor, which is shown approximately for full load conditions, in fig. 6. This loss is sensibly proportional to the square of the current both for concrete and iron shrouded type of reactor.

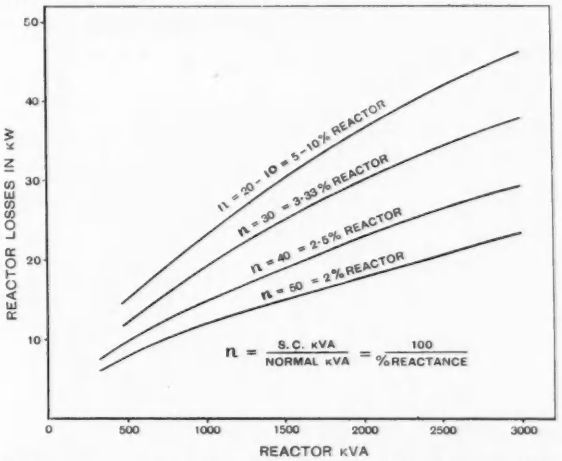

REACTOR LOSSES IN kW
50
40
30
20
10
n = 20 - 10 = 5-10% REACTOR
n = 30 = 3·33% REACTOR
n = 40 = 2·5% REACTOR
n = 50 = 2% REACTOR
n = S.C. kVA / NORMAL kVA = 100 / %REACTANCE
0 500 1000 1500 2000 2500 3000
REACTOR kVA

Fig. 6.—Curves showing kW loss at full load in reactors of various kVA capacity.

Based on the table below, these curves give the percentage circuit power absorbed by the reactor and shows that the loss is not a serious matter.

Table giving approximate reactor loss as a percentage of the circuit kVA.

CIRCUIT kVA	4% REACTOR		10% REACTOR	
	½ load	full load	½ load	full load
1,000	.072%	.29%	.12%	.48%
5,000	.045%	.18%	.068%	.27%
10,000	.032%	.13%	.053%	.21%

TYPES OF REACTOR.

The types of reactor available can be broadly classified in two groups.

(1) Air-insulated reactors.
(2) Oil-immersed reactors.

The air-insulated reactor is generally of the concrete type, examples of which are shown in figs. 7 and 8. The oil-immersed reactor is fundamentally the same as the air-insulated type, but some precautions must be taken to prevent the external field of the reactor cutting the tank and thereby causing high losses and tank heating. There are three main methods of preventing this undesirable effect.

(*a*) By forming a low reluctance magnetic circuit of iron laminations round the reactor coil to carry the external magnetic field. Figs. 13 and 14 show such magnetic circuits. This type is usually known as the iron shrouded reactor.

(*b*) Lining the inside of the tank walls with similar laminations.

(*c*) By fixing short-circuited copper rings to the inside of the tank.

In such a design the external field due to the reactor is prevented from cutting the tank by the opposing field set up by the current induced in the copper ring.

The G.E.C. has standardised the iron shrouded type of oil-immersed reactor which is considered in detail on p. 282.

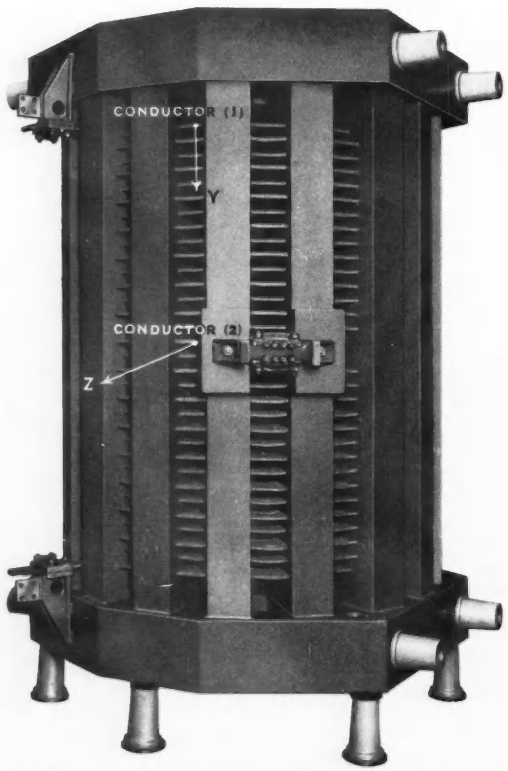


Fig. 7.—Illustrating stresses, axial (Y) and hoop (Z), on the windings of an air-cooled concrete reactor.

Voltage : 11,000. Reactance : 7.5%.
Current : 2,000 amps. Short Circuit Rating : 500,000 kVA.
Throughput : 38,000 kVA. Normal Rating : 2,856 kVA.

RELATIVE ADVANTAGES OF THE CONCRETE AND OIL-IMMERSED TYPE OF REACTOR.

Herewith is given a short summary of the relative advantages of the concrete and oil-immersed type of reactor.

CONCRETE TYPE.	OIL-IMMERSED TYPE.
1. Suitable for indoor use only.	1. Suitable for indoor use or outdoor use.
2. Usually considered suitable only for system voltages up to and including 11,000 volts.	2. Suitable for any circuit voltage.
3. Cheaper in larger sizes (see fig. 9).	3. Cheaper in smaller sizes (see fig. 9).
4. Fire hazard nil.	4. Fire hazard of all oil-immersed apparatus.
5. Maintenance charges negligible.	5. Usual maintenance charges of oil-immersed apparatus.
6. Inspection of condition simple.	6. Inspection of windings difficult.
7. Floor space indoors large and costly.	7. Floor space less and cheaper.
8. Danger of foreign metallic bodies being drawn into windings, or short-circuits due to vermin.	8. Windings protected by tank.
9. External magnetic field may affect instruments.	9. No magnetic field external to tank.
10. No shrinkage of windings to be taken up.	10. Shrinkage of windings should occasionally be taken up.

From this it will be appreciated that both types have very definite advantages and a good case can be made out for the concrete type reactors when the supply voltage does not exceed 11,000 volts and there is sufficient room in the power station for their accommodation.

GENERAL CONSIDERATIONS OF DESIGN.

As a reactor is a redundant piece of apparatus in a supply network, except under fault conditions, it must be considered that the short-circuit duty is its normal duty, and it should be so designed that it is able to withstand repeatedly the high mechanical

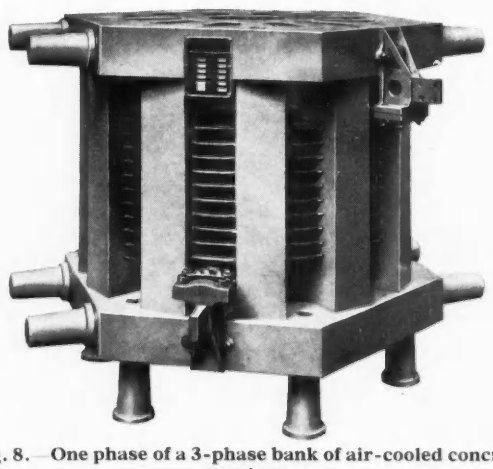


Fig. 8.—One phase of a 3-phase bank of air-cooled concrete reactors.

Voltage : 6,600. Reactance : 4%.
Current : 850 amps. Short Circuit Rating : 242,000 kVA.
Throughput : 9,700 kVA. Normal Rating : 390 kVA.

and electrical stresses which are set up during those conditions with a reasonable commercial factor of safety.

Further, it must be remembered that the reactor is protecting expensive apparatus, and its failure at the critical moment may result in extensive damage to other equipment, with resultant costly repairs.

MECHANICAL.

Under fault conditions the circuit current may rise to a maximum peak value at the first half-cycle of 2·8 times the R.M.S. short-circuit current, as calculated by dividing the circuit voltage by the circuit impedance, and the mechanical stresses should be calculated on the basis of this peak value.

THERMAL.

The physical size and cost of a reactor are greatly influenced by thermal considerations, and the size of conductor chosen has to satisfy three requirements, any of which may predominate.

These three requirements are :

i. The normal temperature guarantee must be met.
ii. The temperature of the conductor after short circuit must not exceed the limiting value.
iii. The cross-section of the conductor must be adequate to withstand the mechanical forces occurring during short circuit conditions.

Since the current density under short circuit conditions has a limiting value in order to comply with the permissible temperature rise, it follows that the current density at normal current depends upon the ratio $\frac{\text{short circuit current}}{\text{normal current}}$ *i.e.*, upon the percentage reactance.

For values of reactance lower than 5%, item ii. is usually the deciding factor for determining the conductor size and hence the cost, while for values of reactance exceeding 5% item i. becomes predominant.

From fig. 11 it can be seen that the cost of a reactor is largely influenced by the ratio, $\frac{\text{short circuit current,}}{\text{normal current}}$ which as already explained determines the conductor cross-section and hence the weight of copper in the reactor. Therefore, when considering costs, this factor must be taken into account as well as the kVA capacity of the reactor. For example, in comparing the relative costs of a 5% and 2% reactor, and assuming a feeder of 50,000 kVA, the capacities of the reactors are 2,500 kVA and 1,000 kVA respectively, then, from fig. 11, the cost of the 2% reactor is approximately 85% of the cost of the 5% reactor, although its kVA rating is only 40% of it.

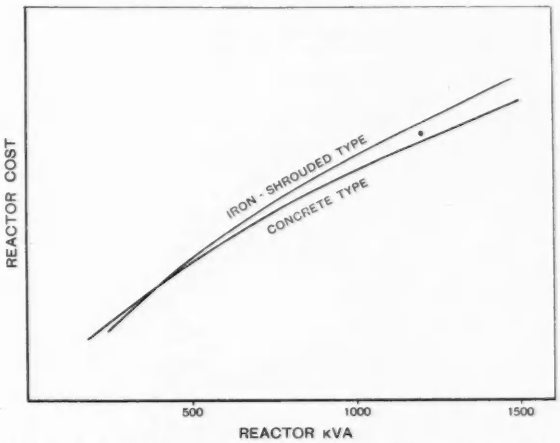


Fig. 9.—Relative cost of concrete and iron shrouded reactors.

For the sake of simplicity, it is the usual practice in reactor design to calculate the thermal conditions under short-circuit on the basis of the R.M.S. short-circuit current, assuming that this current will be maintained for five seconds and none of the heat produced in the windings dissipated. Under such conditions the maximum calculated temperature

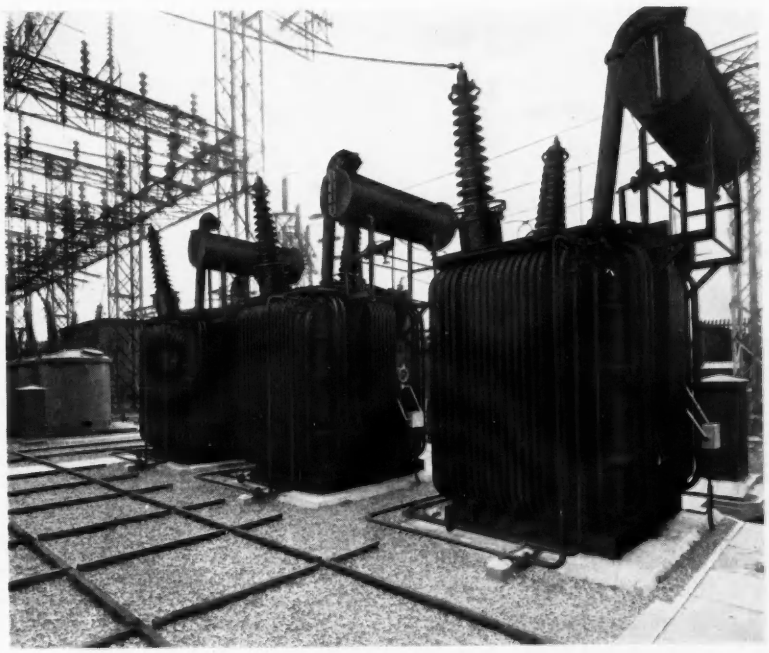


Fig. 10.—132 kV oil-immersed reactors installed at the Ocker Hill Substation (Central England Area) of the Central Electricity Board.

of the windings is limited to 250°C. for reactors with class A, B or C insulation.

The deterioration of class A insulation under the short time application of such high temperatures is very small and practice shows that calculations based on the above assumptions give a good factor of safety.

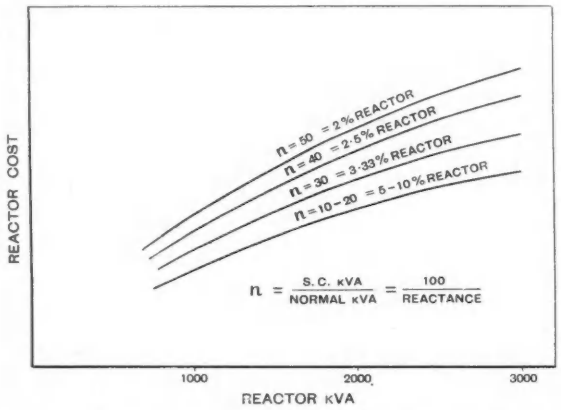

REACTOR COST
n = 50 = 2% REACTOR
n = 40 = 2·5% REACTOR
n = 30 = 3·33% REACTOR
n = 10–20 = 5–10% REACTOR
n = S.C. kVA / NORMAL kVA = 100 / REACTANCE
1000
2000
3000
REACTOR kVA

Fig. 11.—Variation in costs of reactors for different values of kVA and percentage reactance.

It might at first be considered that a higher calculated maximum temperature could be assumed for concrete type reactors, *i.e.*, class A insulation, but this is undesirable due to the high mechanical stress imposed on the windings at the time of short circuit, which has to be withstood by the tensile strength of the copper which is reduced with increase in temperature.

The temperature during short-circuit may be computed by the following approximate formula :

$$T = As\left[\frac{B}{2T_1} + \frac{620E}{B}\right] + T_o$$

where :

T = final temperature in degrees C.
T_o = initial temperature in degrees C.
$T_1 = (T_o + 234{\cdot}5)$
s = time in seconds.
E = ratio of eddy current to I^2R loss at 75°C.
$A = \dfrac{\text{watts per lb. (at } T_o)}{180}$ or
$A = 4{\cdot}6\left[\dfrac{\text{amps.}}{\text{sq. in.}}\right]^2 T_1\, 10^{-11}$
$B = 2T_1 + As$

The following temperature guarantees at normal full load currents, based on transformer practice, are generally given for the purpose of a test rating.

Concrete Type.

Class C insulation—75°C. rise by resistance method.

Oil-immersed Type (Natural Cooling).

Temperature rise of oil—50°C.

Average temperature rise of windings—60°C. by resistance.

In the case of three-phase reactors of the type shown in figs. 17, 18, etc., the average temperature of the windings should be taken with the three phases connected in series.

Assuming a maximum ambient temperature of 40°C. in conjunction with an average daily temperature not exceeding 35°C., the thermal basis of guarantee given above is such that the hottest spot in the windings will not exceed the usually accepted maximum design value of 105°C. under maximum rated load conditions.

DETAIL CONSIDERATIONS OF DESIGN.

Concrete Type.

A concrete reactor is a simple solenoid coil, the turns of which are supported to withstand the large mechanical forces which occur during short-circuit conditions, and spaced sufficiently to prevent a flashover between turns and layers under voltage-surge conditions.

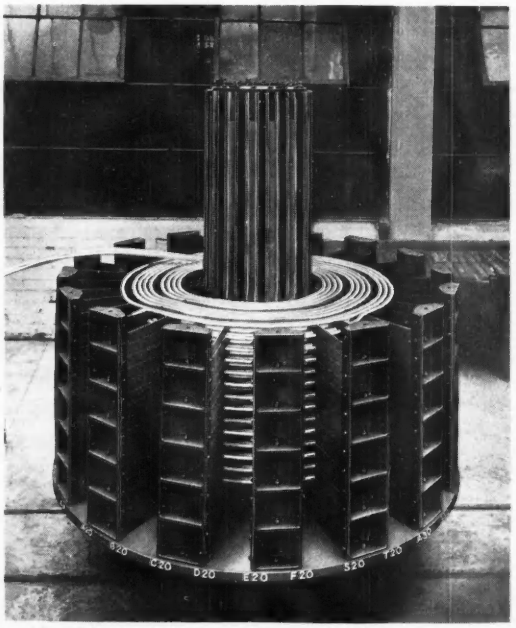


Fig. 12.—Air-cooled concrete reactor shown in fig. 7, in course of winding.

Examples of such reactors are shown in figs. 7 and 8, while the method of winding is shown in fig. 12.

The coil consists of a number of axial layers of concentric turns wound with a stranded conductor consisting of small wires, approximately ·064in. diameter. Unless great care is taken in the design of the conductor and coil the "stray" losses may easily rise to a value as great as that of the I^2R loss. For this reason the wires comprising the conductors

are kept small and the stranded conductor itself is seldom allowed greatly to exceed $\frac{5}{8}$in. diameter.

It is apparent that in order to carry the current it is frequently necessary to use a number of conductors in parallel, and in such cases the coil must be so designed that all conductors are encompassed by an equal magnetic field to prevent circulating currents, hence conductor transpositions are essential. Fig. 12 shows the reactor in fig. 7 during the winding process, and it will be seen that there are four conductors wound in parallel.

During short-circuit conditions the conductor may rise to the limiting design temperature of 250°C. and will thereby increase in length by approximately $\frac{1}{2}\%$, which in the case of the reactor in fig. 8 means ·46 inches per turn, or a total of 16·50in. Unless, therefore, the conductors are solidly gripped by the concrete, linear creepage may occur with a resultant buckling of the conductor between the concrete arms ; this buckling, under high mechanical stress, may give rise to a short circuit between layers or turns. In order to prevent this creepage as well as undue noise under normal

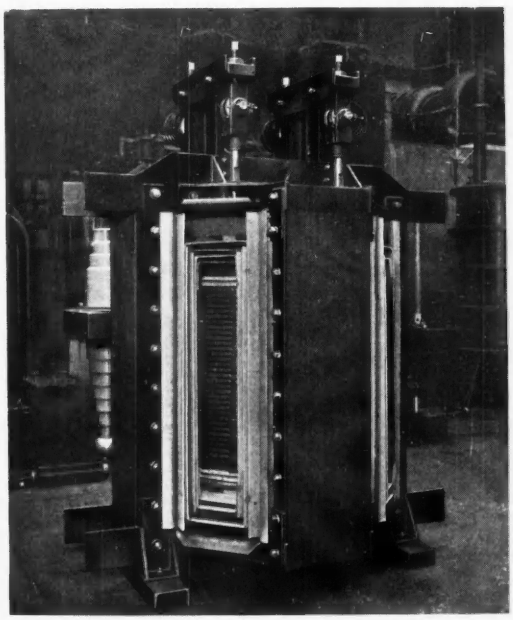


Fig. 13.—Iron shroud for a large high voltage reactor.

current conditions, due to the pulsating force between conductors, the turns are wound in temporary steel formers, as shown in fig. 12, and the concrete arms then formed by forcing liquid cement in between the conductors of sections such as D.20-E.20, F.20-S.20, etc. When set, the concrete arms so formed hold the conductors securely and form a reinforced concrete structure. The concrete mixture is of a special nature and has to be carefully controlled in order to obtain quick setting and maturing combined with adequate strength and freedom from cracking under high temperature conditions.

The normal working voltage between conductor layers is usually considerably less than 1000 volts, whereas the insulation value is about 20,000 volts, thus giving an adequate factor of safety under surge conditions.

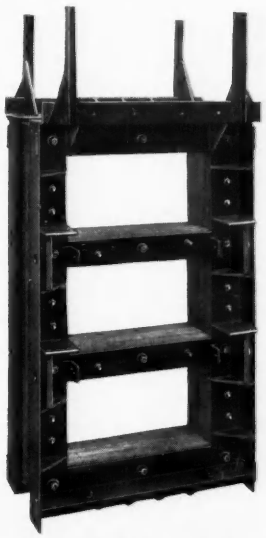


Fig. 14.—Iron shroud for 3-phase reactor.

The direction of the forces in concrete reactors can be considered as two-fold :

(*a*) A force on each conductor tending to compress the coil in an axial direction about a single turn at the centre of the winding.

(*b*) A hoop stress on each conductor in a radial direction tending to enlarge the diameter of each turn.

As an example, the maximum force on the conductors of the reactor shown in fig. 7, the short circuit rating of which is 500 MVA, is as follows :

Stress on conductor (1) in direction $Y = \cdot 35$ tons per sq. inch.

Hoop stress on conductor (2) in direction $Z = 2 \cdot 75$ tons per sq. in.

(*Note.*—The ultimate strength of the conductor is taken as 10 tons per sq. inch).

These forces are restrained both by the conductor and the radial arms, and care has to be taken in spacing the arms to ensure that the bending moment on the unsupported length of conductor is not large enough seriously to reduce the clearance between turns and layers, or to stress the conductor beyond its elastic limit.

It is desirable that short circuit type tests be taken to check design calculations. A type test was made on the reactor shown in fig. 7 at 500,000 kVA which it withstood quite satisfactorily, there being no evidence of cracking either in the concrete arms supporting the winding or in the concrete headers.

Oil-Immersed Type.

As already indicated this type of reactor is in essence a simple choke coil with a laminated iron shroud surrounding it to prevent the flux, under normal load conditions, from cutting the tank and so causing high losses and heating. It follows, therefore,

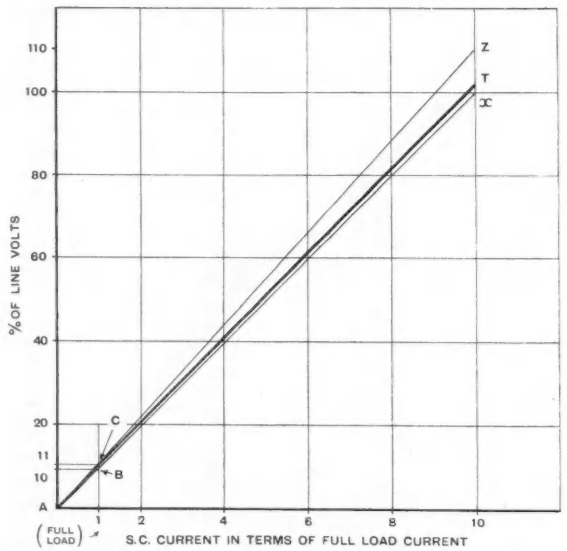


Fig. 15.—Characteristic curve of a 10 per cent iron shrouded reactor.

that at normal full load the flux density in the shroud must be such that the iron loss is reasonably low and the iron unsaturated. A shroud for a three-phase reactor is shown in fig. 14, while one for a large high voltage reactor can be seen in fig. 13.

The shroud slightly increases the reactance of the coil, usually by about 10% at normal full load, with the result that as the iron circuit becomes saturated under short-circuit conditions, the voltage/current characteristic cannot remain a straight line as is the case with a concrete type reactor, but follows a magnetisation curve superimposed on a straight line, as explained below.

Referring to fig. 15, let x be the required voltage drop under short-circuit conditions. The voltage drop across the coil without any shroud will be a straight line *ABx*. Owing to the reactance of the coil being increased due to the shroud, the voltage at normal full load current will be 10% higher as shown at *C*, the characteristic *AC* being sensibly a straight line, as the flux density is low.

If the iron circuit did not become saturated but retained the same permeability at high flux density, the characteristic curve *AC* would continue as a straight line, *ACZ*, and the reactive drop would be 10% higher than required under short-circuit conditions; but such is not the case. When saturation occurs the characteristic, *CZ*, bends over and then continues parallel to curve *Bx*.

It is normal practice with the flux densities ordinarily used to assume that saturation of the iron occurs shortly after full load, when the characteristics of the iron shrouded reactor will become *ACT*, giving a test value under short-circuit conditions two or three per cent higher than actually required. If this higher reactance is considered undesirable the whole characteristic can, of course, be lowered by designing the coil for a slightly lower natural reactance.

The construction of the iron shroud follows normal transformer practice, the joints between the laminations being interleaved and the whole held tightly between side plates, pulled together by insulated bolts.

To ensure a uniform distribution of flux in the shroud of a three-phase reactor it is necessary to reverse the direction of winding of the coil occupying the centre position in the shroud.

Besides shielding the tank from the flux, the shroud serves as an excellent base to which a structure can be fixed for positioning the coils and bracing them against the large hoop stress which occurs under short-circuit conditions. The radial adjustable bracing clamps can be seen in figs. 17, 18 and 19.

Again, under short-circuit conditions, there is a large stress between the coil groups of the three phases which produces a tendency to

Fig. 16.—Six of the 33 oil-immersed shrouded type reactors supplied to Rotherham Corporation for installation at the Prince of Wales Power Station.

Voltage: 6,600. Reactance: 1.97%.
Current: 200 amps. Short Circuit Rating: 100,000 kVA.
Throughput: 22,800 kVA. Normal Reactor Rating: 450 kVA.

compress them and cause shrinkage in an axial direction ; although the coil groups are pressed and matured before assembly, further shrinkage may occur if the reactor has to withstand many severe short circuits, and for that reason axial adjusting bolts are provided.

It is particularly necessary to clamp the coil and uprising leads securely as the forces on them are large and difficult to determine by calculation. Experience has shown that it is desirable to type test each construction under short-circuit conditions and this was done in the case of the reactors shown in figs. 13 and 17. Fig. 21 shows the oscillograph record of the short-circuit test on the 132 kV reactor seen in fig. 13.

During the short-circuit type test on the reactor shown in fig. 13 tests were made at gradually increasing loads, and it was noticed that the "hum" due to the forces became less as the load was increased. The reason for this was not at first clear, but an inspection of the reactor after the test showed that the forces compressing the coil stack had shrunk the windings by about $\frac{3}{8}''$ which had been taken up by the automatic non-return adjustable coil clamps, thus producing a more highly compressed coil, the turns and coil sections of which were less subject to vibration under the high stresses which occurred.

The general insulation of both high and low voltage reactors closely follows the lines of good transformer practice and hence requires no special comment, except that of emphasising the necessity of making sure that the insulation will not fail due to mechanical causes.

For reasons of floor space and economy, it is usual to design small and medium size three-phase reactors as single units in one tank, as shown in fig. 19; this, however, becomes impractical for large high-voltage reactors owing to mechanical instability due to their height, the mechanical stress between phases, and the difficulty of securely bracing the

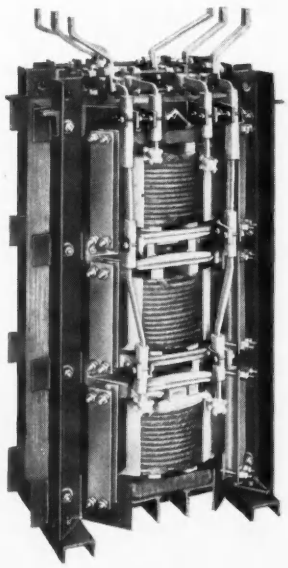


Fig. 17.—3-phase oil-immersed shrouded reactor.

Voltage : 6,600. Reactance : 5%.
Current : 437 amps. Short Circuit Rating : 100,000 kVA.
Throughput : 5,000 kVA. Normal Rating : 250 kVA.

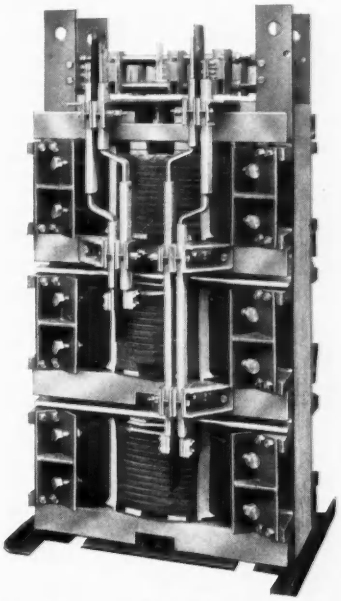


Fig. 18.—3-phase oil-immersed shrouded reactor.

Voltage : 11,000. Reactance : 5%.
Current : 525 amps. Short Circuit Rating : 200,000 kVA.
Throughput : 10,000 kVA. Normal Rating : 500 kVA.

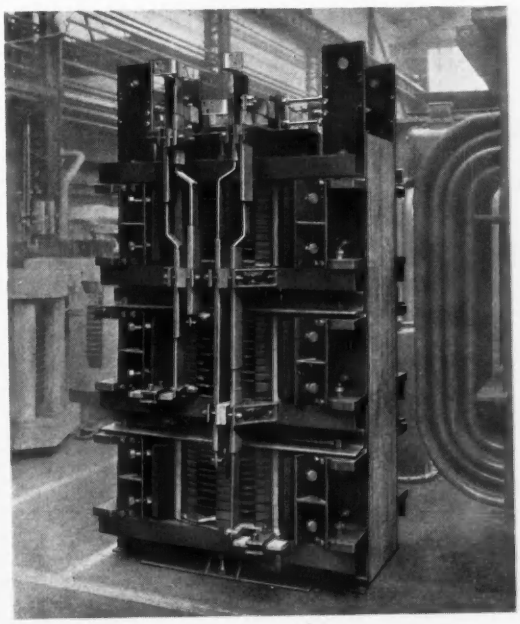


Fig. 19.—Iron shrouded 3-phase reactor for Norwich Corporation.

Voltage : 6.600. Reactance : 10%.
Current : 1.000 amps. Short Circuit Rating : 114,000 kVA.
Throughput : 11,400 kVA. Normal Rating : 1,140 kVA.

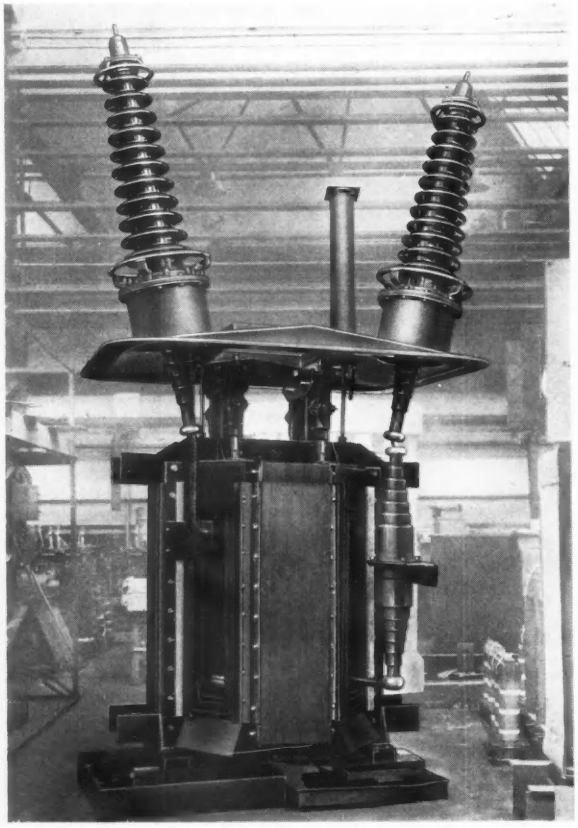


Fig. 20.—One phase of a 3-phase bank of oil-immersed shrouded type reactors.

Voltage: 132 kV.	Reactance: 10%.
Current: 218 amps.	Short Circuit Rating: 500,000 kVA.
Throughput: 50,000 kVA.	Normal Reactor Rating: 5,000 kVA.

six high voltage leads in a confined space. When these limitations arise, three-phase reactors are made in single units, generally as shown in figs. 10, 13 and 20.

SITE CONDITIONS.

Where concrete reactors are used, it is usually necessary, on account of space limitations, to install the three reactors of a three-phase bank close to one another; hence a considerable force of attraction or repulsion occurs during short circuit conditions due to the interaction of the separate reactor fluxes. Such forces are resisted by the massive construction of the reactors and also by means of insulated struts between the units.

It will be appreciated that the strong magnetic field set up by a reactor tends to draw any foreign matter of a magnetic nature such as loose bolts, wire, etc., into the windings; if this happens during operation, a short circuit will occur between turns or layers. Such a short circuit usually causes ionization of the uprising air which may result in a flashover between all the turns and a resultant power arc across the whole reactor. This tendency is increased at the time of a short circuit by the greater voltage between turns and layers and the greater force of attraction on the foreign matter.

This hazard can be minimized by using suitably treated asbestos-braided conductors, but such protection normally increases the cost of a reactor by approximately 15%, and it may be considerably greater if the design temperature of the reactor in question is already at the maximum allowable

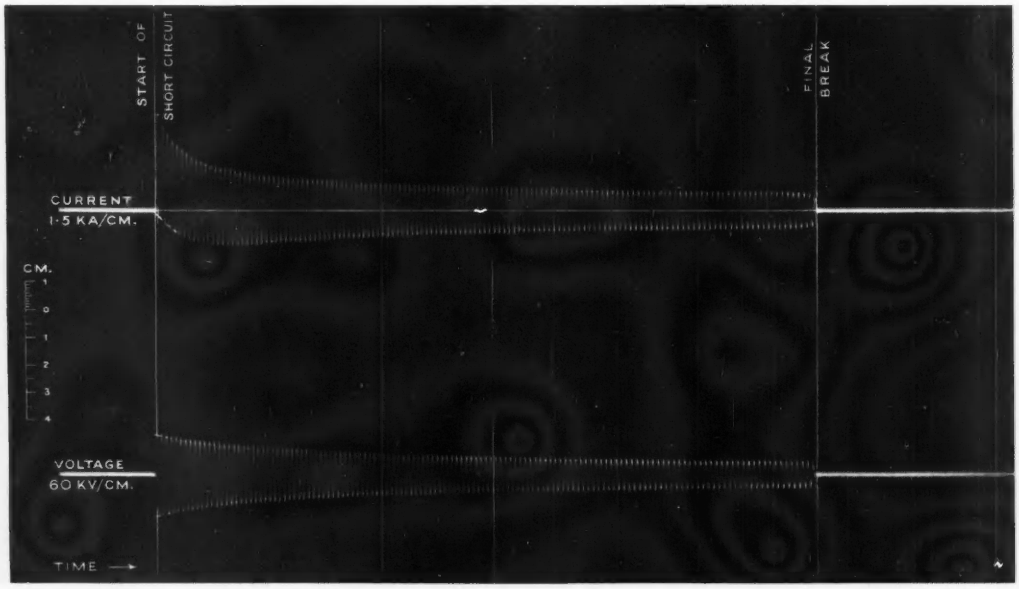


Fig. 21.—Oscillogram of a 500 MVA short circuit type test on the 132 kV reactors shown in Figs. 10, 13 and 20.

figure, in which case the conductor area has to be enlarged to compensate for the temperature gradient caused by the insulation on the conductor.

The expense to be incurred in reducing the hazard referred to has to be considered in conjunction with the situation of the installation, and the care that will be taken to prevent foreign matter from entering the reactor enclosure. Although the danger is a real one, few reactors have been called for with this refinement, and the author has not seen a breakdown from this cause. Fig. 22 shows a bank of concrete reactors in a suitable enclosure.

When considering the choice of an installation site for concrete reactors, it is necessary to observe that there is no steelwork in close proximity to the reactor coils, otherwise heating of such steelwork will occur, and the reactor losses will be increased. There is also the possibility that the design characteristics may thereby be altered. Hence the nature of the building and the position of steel stanchions have to be considered, and as an approximate guide to the necessary clearance between the reactor coil and any steelwork it may generally be assumed that a clearance equal to half the outside diameter of the coil is adequate. With oil-immersed reactors it is obvious that there are no such restrictions on the choice of site.

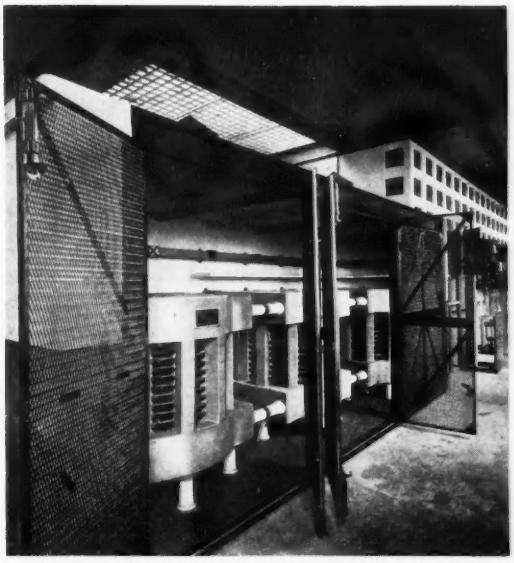
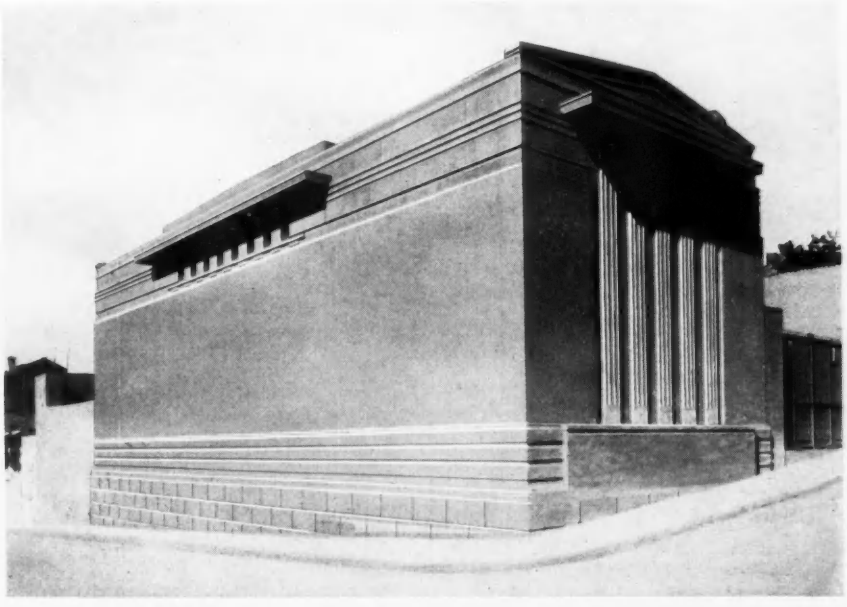


Fig. 22.—Concrete reactors installed at Nechells Power Station, Birmingham.

Pumpless Air-cooled Mercury Arc Rectifier Equipment for Athens Piraeus Electricity Co., Ltd.



One of the sub-stations in Athens, housing a twin cylinder G.E.C. pumpless air-cooled steelclad mercury arc rectifier unit having an output of 625/573 kW at 600/550 volts. A total of six single cylinder and two twin cylinder units, together with rectifier transformers and remote control gear, have been supplied to this Company to the specifications of Whitehall Securities Corporation Ltd., London.

The Concentration of Minerals by Flotation.

Part III.

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CONDITIONING TANKS.

IN parts 1 and 2 of this series of articles the action of the various reagents used in flotation on the constituents of an ore has been described. It has been shown how the valuable minerals are rendered floatable by the use of appropriate promoting reagents and any unwanted minerals are prevented from floating by means of depressors, the worthless rock, or *gangue*, being naturally unfloatable. Promoting and depressing reagents generally need an appreciable period of time in contact with the minerals in order to perform their functions. If the contact time is not critical, they are added at some point in the grinding circuit ahead of the flotation section. But when a definite critical period of contact is found to be necessary, the pulp from the grinding section is passed through a conditioning tank[1] before entering the flotation machines, and the reagents are introduced into the circuit at that point.

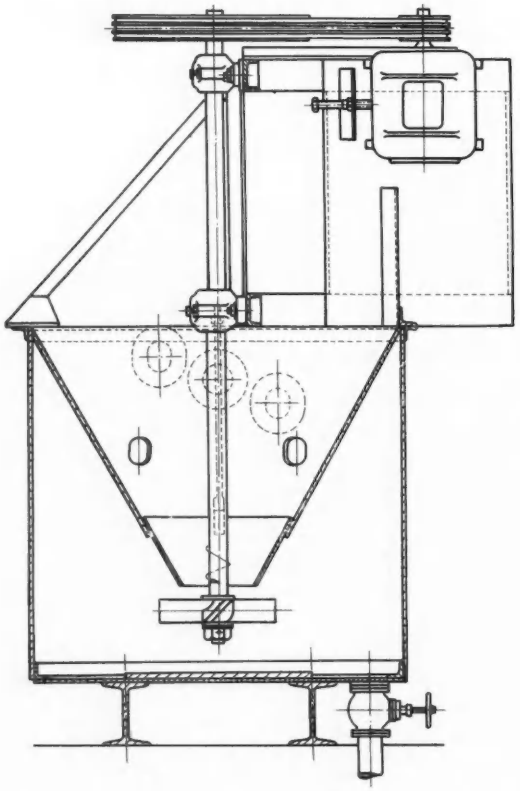


Fig. 1.—Fraser & Chalmers conditioning tank.

The type of tank employed is shown in fig. 1. It has a cylindrical body containing an inner conical compartment, both made of steel plates, with an impeller revolving near the bottom under the lower end of the cone. The impeller has four blades set at 45° and is rotated so as to draw pulp down the cone and throw it outwards into the main body of the tank. The stream of pulp from the grinding section, containing 20–30 per cent of solids, is fed into the top of the tank at any convenient place and there meets the reagents, which are introduced at the same point. The mixture is drawn down the cone by the impeller and forced into the outer compartment. It rises up the sides and passes through the holes into the conical section, where it joins the incoming stream of pulp, circulating in this way until it is finally discharged through the outlet in the side of the main tank after undergoing the appropriate conditioning period. Although there is always the possibility in a tank of this design that a particle of mineral may pass direct from the cone to the outlet without circulation, short-circuiting does not appear to take place to any extent, and the pulp as a whole receives the correct amount of conditioning. The size of tank needed to give a particular period of contact depends on, and can be calculated from, the volume of pulp passing through the plant, which is always kept reasonably constant. A series of outlet holes is provided, one above the other, in the side of the cylindrical portion, so that the time of contact can be varied within small limits if required.

1. See Part I., fig. 2, for its position in relation to the other machines.

From the conditioning tank the pulp passes direct to the flotation machines, where the valuable minerals are separated from the remainder of the pulp in the form of a concentrate.

FLOTATION MACHINES.

There are a dozen or more different sorts of flotation machines in use at the present day. As a description of them all would occupy too much space, two types have been selected to illustrate the general trend of design, *viz.*: the Minerals Separation and Kraut machines.

The Minerals Separation, or M.S. machine, which is shown in fig. 2, is one that has been very popular during the past 20 years. It consists of a series of any number of square cells, made of wood or mild steel plate, with a cast iron impeller rotating in the bottom of each over a pulp transfer passage and an air inlet pipe. The impeller is of the enclosed type with a circular opening in the underside and has four curved blades set at an angle of 45°. It is fixed to the lower end of a vertical driving spindle and rotates at a peripheral speed of 1,450 ft. per min. Baffles placed over the impeller confine the agitation to the lower part of the cell, which is protected from wear by cast iron lining plates.

The pulp enters the machine continuously through a transfer-passage under the bottom of the first cell, and is drawn up by the suction of the impeller and thrown out into the zone of agitation in the lower part of the cell. A stream of low-pressure air, controlled by a regulating valve, is blown into the cell under the impeller and disseminated throughout the lower zone as a cloud of minute bubbles by the violence of the agitation there. The particles of ore, including the valuable mineral, are thus in continual collision with the bubbles as they rise through the pulp; some of the mineral sticks to and coats the bubbles, but most of the gangue that is caught up drops out almost at once. The mineral-laden bubbles rise through the quieter upper zone above the baffles, dropping on the way particles of gangue still held by mechanical entanglement, and collect on the surface of the pulp as a froth, which is scraped as fast as it forms into a launder fixed to the front of the machine. The tailing, containing unfloated mineral and unfloatable gangue, flows out through a slot at the back of the cell and over an adjustable weir, from which it drops into a transfer-passage and is drawn up by the impeller into the next cell, where a further portion of the valuable mineral is floated in the same way as before. The pulp passes from cell to cell in this manner until all the valuable mineral has been removed, the number of cells being regulated so that a barren tailing is discharged from the last one.

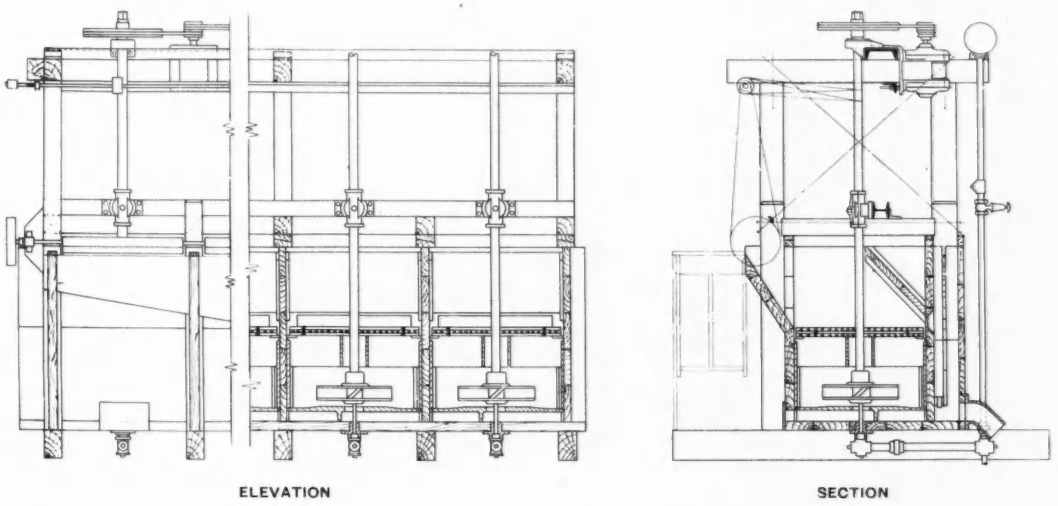


Fig. 2.—The M.S. flotation machine.

The M.S. machine works well in practice, but it has certain disadvantages inherent in its design; *viz.*, (1) a really quiet upper zone cannot be obtained with the lower zone in violent agitation ; (2) power is wasted in using an agitating impeller as a pump to draw up pulp into the cell ; (3) in the event of a sudden stoppage the impellers become choked almost at once by settling particles of ore, and the machine cannot be re-started without first emptying out the whole of its contents.

One method of overcoming these difficulties is to confine the agitation to a special chamber in the middle of the cell, and to circulate the pulp through it. The Kraut flotation machine is designed on this principle. Its construction can be seen from figs. 3 and 4. It is made in 1-cell, 2-cell, and 4-cell units, which can be bolted together to form a machine of any required length. Fig. 5 shows two of these units (2-cell and 1-cell) as installed in the concentrating plant of the Weardale Lead Co., Ltd., for the flotation of galena (lead sulphide). The cells are made of mild steel plate, the back being extended upwards to provide support for the rotor mechanism and the driving motor. The chamber in which agitation and aeration are effected is placed vertically in the middle of the cell, and consists of a rotor in the form of a helical screw revolving in a stationary cylinder. The rotor is attached to the lower part of a hollow shaft, the upper part of which is carried by two ball bearings in a dust-proof watertight housing. The helical screw is made up of four segments, covered with rubber on the outside, which are bolted to spiders on the shaft in such a way as to leave narrow vertical slots between the segments. The rotor is closed top and bottom, and holes are drilled in the hollow shaft so that air can pass from the shaft to the slots. The stationary cylinder is

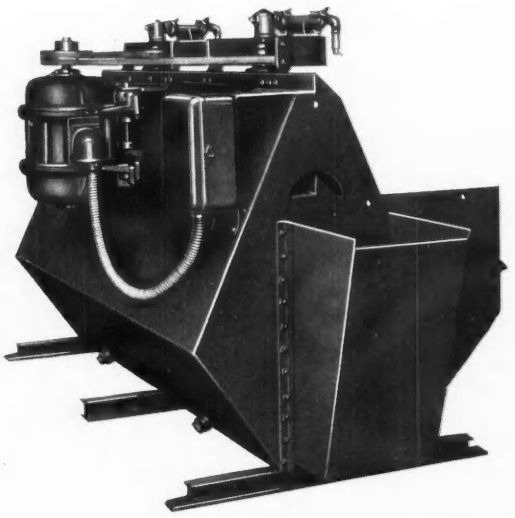


Fig. 4.—Kraut flotation machine, side view, showing feed box and drive.

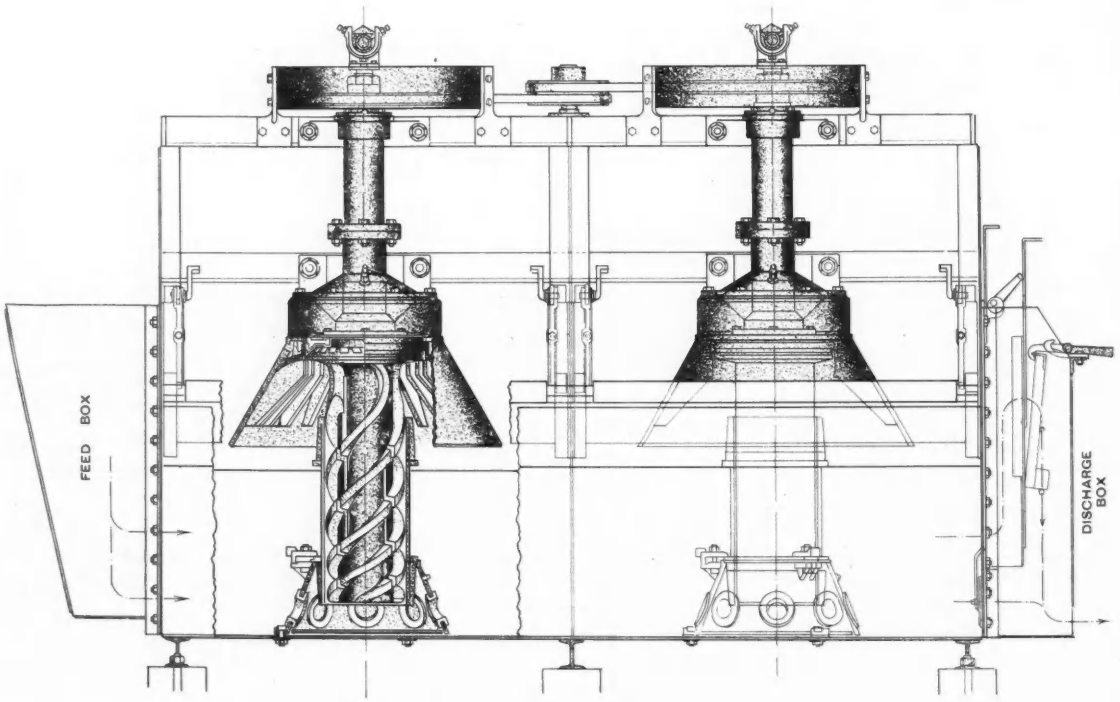


Fig. 3.—Kraut flotation machine, front view.

lined with rubber on the inside and rests on a conical base which has eight inlet holes for entry of the pulp. The rotor-cylinder combination forms a powerful screw pump when the helices are turning at a high speed (1,700—1,800 peripheral ft. per min.) in the direction required to draw pulp upwards through the chamber. The helices are given an increasing lead upwards so as to create a suction which draws in air through the slots from the hollow shaft. The shaft is plugged at the bottom and is fitted with a valve at the top for controlling the volume of air admitted. The shafts are driven in pairs by vertical motors secured to the superstructure at the back of the cell, the power being transmitted by V-belts and grooved pulleys. The upper end of the stationary cylinder is overhung by a bell-shaped hood, rubber-covered on the inside, the rubber lining being made with radial fins or baffles.

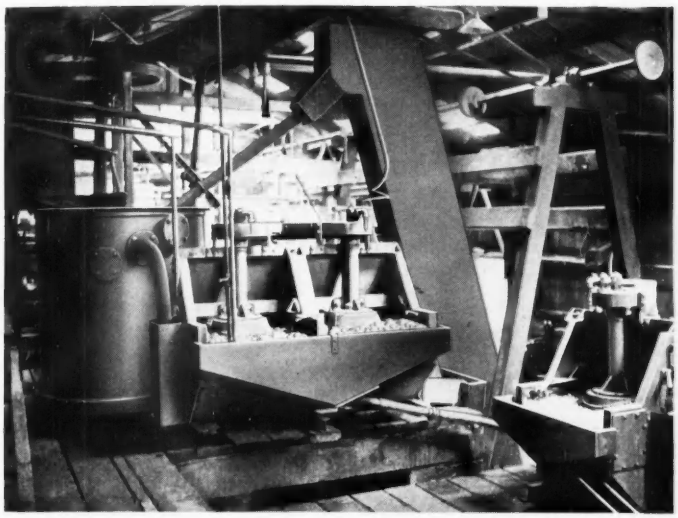


Fig. 5.—Flotation plant of Weardale Lead Co., Ltd., Northumberland, showing Fraser & Chalmers conditioning tank and Kraut flotation cells, two for roughing and one for cleaning. The flotation plant recovers galena (lead sulphide) from the tailings of the gravity concentration plant.

The pulp enters the first cell through a feed-box, and passes along the length of the machine, circulating continually through the rotor-cylinder chamber, where the intensity of the agitation breaks up the air drawn in through the slots into minute bubbles and disseminates them throughout the pulp. The volume of air is regulated in each cell according to requirements by the valve at the top of the hollow shaft. The stream of pulp is discharged from the top of the cylinder into the hood, the fins stopping the whirl imparted by the rotating screw, and passes downwards into the body of the cell. The bubbles, partly covered with mineral, travel upwards to the surface, collecting more mineral on the way, and settle on the top as a froth, which is forced by the continuously rising stream of bubbles over the discharge lip along the front of the machine into a launder placed to receive it; it is so voluminous that paddles are not needed to scrape it over the lip. The pulp passes from cell to cell through slots in the partitions, circulating during its passage through the rotor-cylinder chamber, as described above, until all the floatable mineral has been taken out in the froth and a barren tailing overflows the discharge weir at the end of the machine.

FLOTATION CIRCUITS.

In order that flotation may be a profitable process, it is normally necessary to recover in the final product (the mineral concentrate) 90 per cent or more of the valuable mineral in the ore; that is, it is necessary to ensure that no more than 10 per cent of the mineral escapes in the tailing. This result is achieved by filling the pulp in the flotation machine with a mass of bubbles so closely packed that particles of gangue are inevitably carried up in the froth by mechanical entanglement, and the concentrate produced in this first, or *roughing*, operation often contains as much as 50 per cent of gangue, though the tailing is substantially free from mineral. The

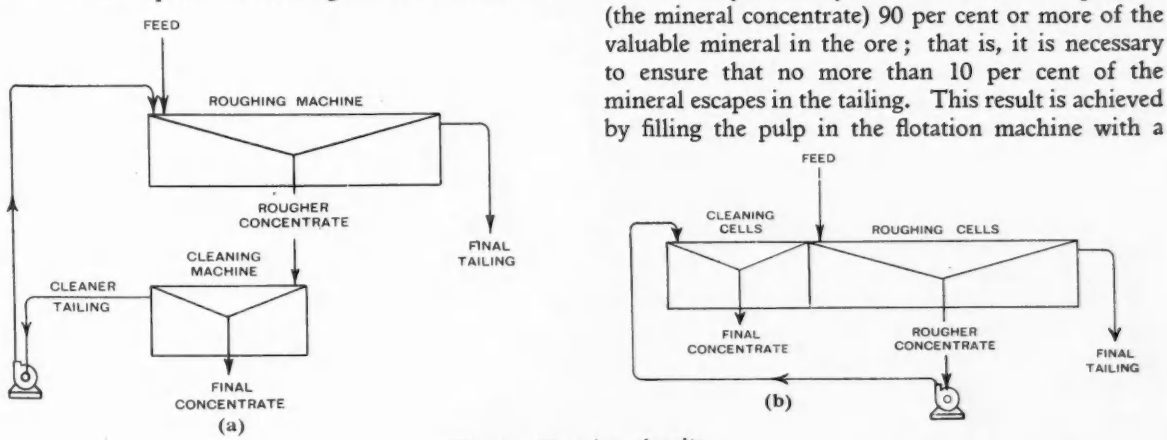


Fig. 6.—Flotation circuits.

rougher concentrate, as it is called, is therefore re-treated in a second, or *cleaning* machine, which is usually one-quarter to one-half the size of the roughing machine. The operation is shown diagrammatically in fig. 6a. The froth is diluted, as it enters the machine, with 4 to 6 times its weight of water, and flotation is effected with the smallest possible volume of bubbles. By these means the chance of gangue particles being carried up by mechanical entanglement is reduced to a minimum. A clean mineral concentrate is produced, but the tailing, nearly always contains a substantial proportion of unfloated mineral and is therefore returned to the head of the roughing machine. Thus a circulating load accumulates containing the least floatable mineral and the most floatable gangue. It does not increase indefinitely, however, as the conditions in the circuit are such as to favour the flotation of the wanted mineral and the depression of the gangue, and a condition of equilibrium is soon reached, the various constituents finding their way into concentrate or tailing after a few journeys round the circuit.

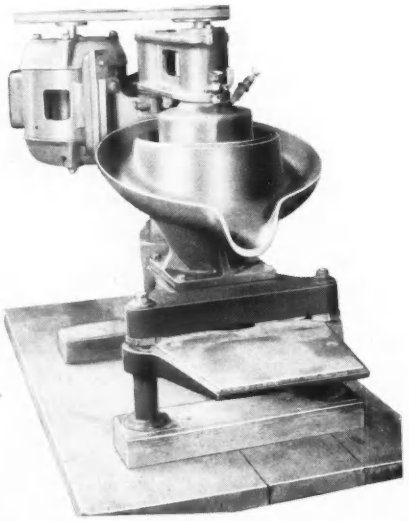


Fig. 7.—Kraut laboratory flotation machine.

If the concentrate from the re-treatment machine is still not clean, as sometimes happens when the gangue is unusually floatable, the cleaning operation must be repeated in a third, or *re-cleaning* machine. This should yield a concentrate of the highest possible grade; further stages of cleaning are seldom found to effect a measurable improvement.

A common alternative arrangement of the cleaning circuit is shown in fig. 6b. Here the rougher concentrate is pumped to a cleaning machine placed ahead of the roughing section. Since the cleaner tailing must be returned to the first roughing cell, the cleaning and roughing machines can conveniently be bolted together in one unit as shown. This method is useful when there is insufficient fall to enable the rougher concentrate to flow by gravity to the cleaning machine.

Every ore presents its own problem in flotation, and variations of the circuits described above may be needed to meet special circumstances. But whatever the variation adopted, one of the arrangements shown in fig. 6 forms the basis of nearly every flotation circuit.

LABORATORY TESTING FOR FLOTATION.

No two ores behave alike in flotation, and it is not possible to design an installation for an ore from a particular mine or deposit without first carrying out small-scale laboratory tests to find out what equipment is required. The machines in which the tests are carried out are similar to those used in actual practice, but they are not necessarily small-scale models of them. For laboratory testing purposes it is not an exact reproduction of the full-size machine on a small scale that is required, but an exact reproduction of the results obtainable in the full-size machine. Consequently, there is often a considerable difference in the design of the two models; compare the Kraut laboratory flotation machine in fig. 7 with those in figs. 3 and 4. Another point of difference between full-scale practice and laboratory

Fig. 8.—Some of the flotation equipment at the G.E.C. Research Laboratories.

testing is that the former is a continuous operation while the latter is carried out with small batches of ore. The two can be readily correlated, however, because the ratio between the time of treatment in both cases is constant. For example, if an ore requires, say, 6 minutes in a laboratory flotation cell to produce a tailing free from mineral, then the flotation time necessary to produce the same result under similar conditions in a full-size machine will be 6 minutes multiplied by a known factor (usually 1·2—1·5), which is constant for a given machine irrespective of the ore being treated.

The type of equipment employed for testing can be seen in figs. 8 and 9, which show two views of the ore dressing laboratory at the G.E.C. Research Laboratories, Wembley. Here all problems connected with ore dressing, including flotation, are investigated, and the data obtained for the design of complete installations.

The investigation of any ore submitted to the Research Laboratories is always preceded by an examination of its mineralogical characteristics before flotation or other tests in small-scale machines are started. The chief metallic and rock-forming minerals are first identified as far as possible by simple chemical tests and by microscopic examination of the crushed ore and of polished sections, a variety of instruments being available for the latter purpose in the microscopy department. These investigations are supplemented by spectrographic analysis, by which all the metals and most of the metalloids present in the ore can be detected. The apparatus used, which is illustrated in fig. 10, is a large Hilger quartz spectrograph with suitable auxiliary apparatus for exciting the spectrum. The method of procedure consists in photographing the spectrum of the ore in juxtaposition with that of a standard of known composition, one of the most useful being a mixture termed *R. U. Powder*. This mixture, which contains over fifty elements, is specially prepared in the Research Laboratories. By comparing the lines of the known with those of the unknown spectrum the component elements of the latter can be determined. The analysis is essentially qualitative, but the main constituents are readily distinguishable from the elements that occur in unimportant amounts, and these again can be distinguished from minute traces. The above methods generally enable the mineralogical constitution of the ore to be determined with reasonable accuracy. The proportions of the various constituents are then determined quantitatively in the chemical laboratory. It should be noted that the preliminary spectrographic analysis saves the time and expense of unnecessary chemical determinations by indicating in one operation the elements of importance of which quantitative analyses must be made.

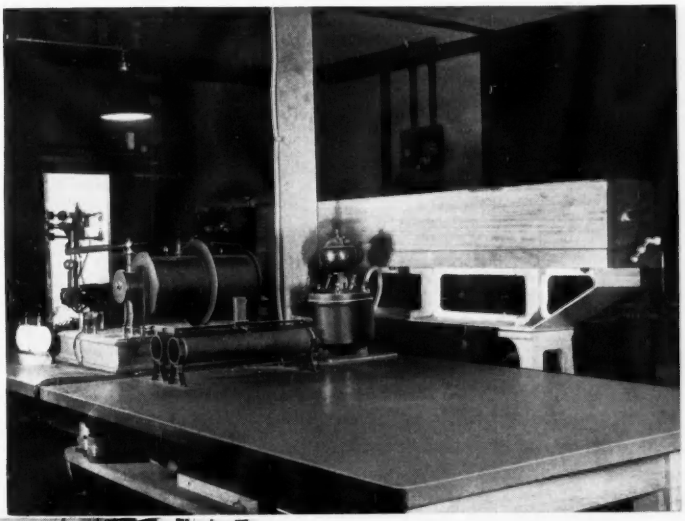


Fig. 10.—Laboratory spectrographic equipment.

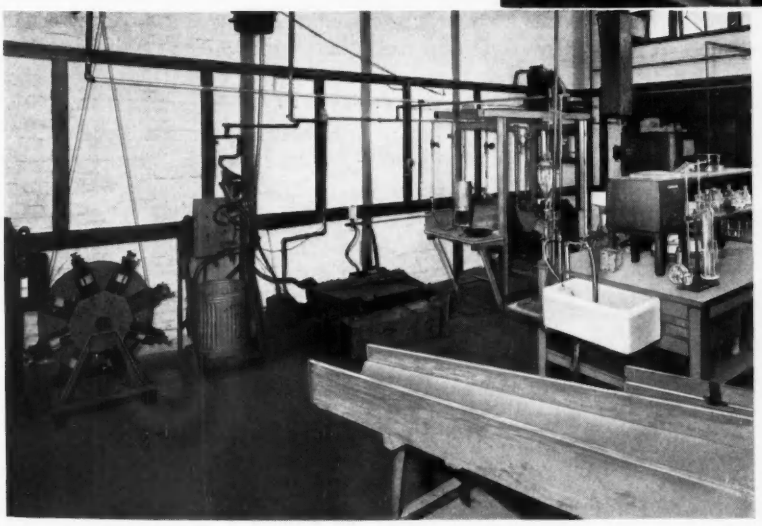


Fig. 9.—Some of the laboratory gravity concentration equipment.

It sometimes happens that the composition of one or more of the minerals is still in doubt. In such a case a small quantity is isolated and subjected to X-ray examination. The equipment employed, which is illustrated in fig. 11, was constructed in the Research Laboratories. It consists of an X-ray diffraction apparatus designed for the Debye-Scherrer powder method of analysis, the diffraction pattern for the substance under examination being recorded photographically. Given the elements

present in the substance, which are found by separate spectrographic and/or chemical analyses, its identity as a definite compound or as a mixture of two or more compounds is determined by the nature of the

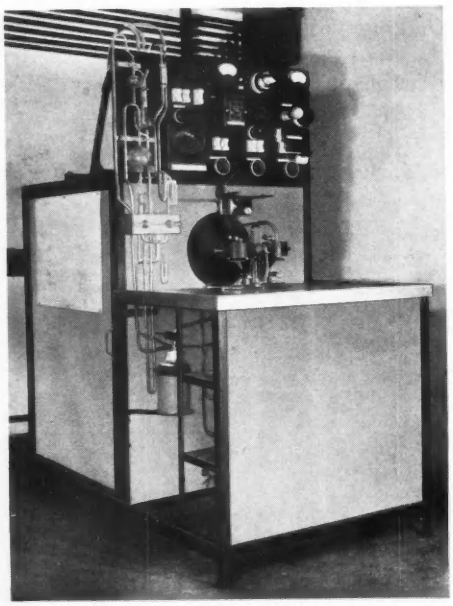


Fig. 11.—Equipment for X-ray analysis at the G.E.C. Research Laboratories.

pattern obtained. The use of X-ray analysis in mineralogical work is well illustrated by an instance which occurred in the investigation of a copper-zinc ore. The principal mineral was put down as chalcocite (Cu_2S) in the preliminary microscopic examination, but subsequent spectrographic analysis revealed the presence of zinc and arsenic, from which it was assumed that it was an intercrystallized mixture of tennantite ($4Cu_2S.As_2S_3$) and sphalerite (ZnS). No method could be found, however, for separating the sphalerite from the tennantite either by flotation or by any other mechanical process. Microscopic examination of a section gave no clue to the structure of the mineral. A sample was therefore analysed by the X-ray method. It was found that free sphalerite was not present, but the substance consisted of a homogeneous compound having the crystalline structure of tennantite with part of the Cu_2S replaced by ZnS, its formula approximating to $5Cu_2S.2ZnS.2As_2S_3$. Since the constituents of such a compound can only be separated by a chemical process, no further time was wasted on flotation tests.

When the nature of the minerals and their mode of occurrence in the ore have been determined, theoretical considerations plus experience with similar ores usually suggest a likely method of flotation, and small-scale tests are started with batches of ore 1–2 lb. in weight. The ore is first crushed dry to about 2 mm. size in a jaw-breaker followed by a roll-crusher, and then ground in water to the required degree of fineness in a small laboratory ball mill, two of which can be seen in fig. 8. The pulp from the ball mill is transferred to the Kraut flotation machine (figs. 7 and 8), water being added to bring it to the correct dilution, and the valuable minerals are floated off and cleaned in a subsequent operation in the same machine. Observations during the test and examination of the products usually lead to modification of the reagents or method of flotation, and further tests are carried out on the lines suggested until the desired result appears to have been attained. Chemical analyses of the products are made at this stage to find out whether they are of the required grade; if they are not, the batch tests are continued until the results are satisfactory.

It is generally possible to design a flotation plant from the data given by laboratory tests. When a new process is being developed, however, testing work is usually continued in a specially built pilot-plant, *i.e.*, in a plant containing the smallest machines capable of continuous operation; its capacity is usually 1–2 tons per hour. There outstanding problems are solved and all the information obtained that is required for the design of a full-size installation.

FLOTATION IN INDUSTRY.

The position of flotation in industry can best be summed up by considering it in relation to the mining industry, of which it is an integral part. No official figures are available of the tonnages of ore concentrated annually by flotation. It is estimated, however, that the production of non-ferrous base-metal ores, exclusive of alluvial tin-bearing gravels, which are in a different category, totals something like 125 million tons per annum. Of this amount, about 100 million tons are concentrated by flotation with an expenditure (mining plus concentrating) of £80,000,000 or more. The majority of the mines are completely electrified, and electrification of the remainder appears to be only a matter of time.

While the mining industry is thus dependent on the electrical industry for a part of its supplies, the reverse is true in a much greater degree. At least 90 per cent of the raw materials used in the manufacture of electrical equipment is derived from minerals or rocks which occur as deposits in the earth's crust and have to be extracted by mining or quarrying. Of these raw materials, iron is the only one required in large quantities, in the production of which flotation plays no part. But virtually, the whole consumption of copper and 90 per cent of the lead, zinc and nickel come from mines which employ flotation as the first step in the production of the refined metal.

Diesel-Electric Ferry for the Clyde.

By C. WALLACE SAUNDERS, M.I.Mar.E., A.M.I.C.E., A.M.I.E.E.
Manager, Marine Department,
and H. J. COATES,
Switchgear Department, Witton Engineering Works.

It is of particular interest that the Diesel-electric ferry described in this article has been called upon to deal with the exceptionally large volume of heavy traffic resulting from the Empire Exhibition and the launching of the "Queen Elizabeth." The duty demanded of her since she was put into service is probably the most arduous ever experienced by electrical propelling machinery.

As an indication of its severity, it may be mentioned that the ferry is running 18 hours a day, 6 days a week, which is a total of 5,600 hours a year; and as the trip takes only 2 minutes, the propelling machinery is thus continually "backing" and "filling" from full ahead to full astern. The controllers are operated over 3,000 times a day, or almost one million times a year. Furthermore, the generating sets are slowed down from 500 r.p.m. to an idling speed of 150 r.p.m. at the end of each trip and brought up to speed again just before leaving.

Since going into commission in May, 1938, the ferry has not missed a single trip—an outstanding tribute both to the electrical equipment and the Diesel engines.

AN interesting application of the Diesel-electric drive is embodied in the Clyde Vehicular Ferryboat No. 4 which plies between Govan and Partick. The ferry, which is of a type peculiar to the Clyde, and is employed for vehicular and passenger traffic across the river, was built to the requirements of the British Corporation by Ferguson Brothers (Port-Glasgow), Ltd., for the Clyde Navigation Trust under the supervision of Major. W. A. Oliphant, Chief Mechanical Engineer.

Fig. 1 shows a general view of the ferry which possesses many unusual features in order to enable the duty demanded of her to be discharged satisfactorily. The vessel is 82ft. long, 44ft. wide and has a depth to the main deck of 12ft. The time taken for her passage across the river, which is 550ft. wide at this point, is two minutes.

The ferry is double-ended and is equipped with two propellers at each end, mounted on two through shafts which are driven through gearing by the two main propulsion motors. In normal service all four propellers are used, the two forward ones acting as

Fig. 1.—The Diesel-electric ferryboat of the Clyde Navigation Trust plying between Govan and Partick.

tractors. No rudders are fitted, the steering being carried out by varying the speed and direction of rotation of the propellers. This enables the ferry to be manœuvred conveniently in all circumstances, and it is possible to turn her completely round on her own axis in a very short space of time.

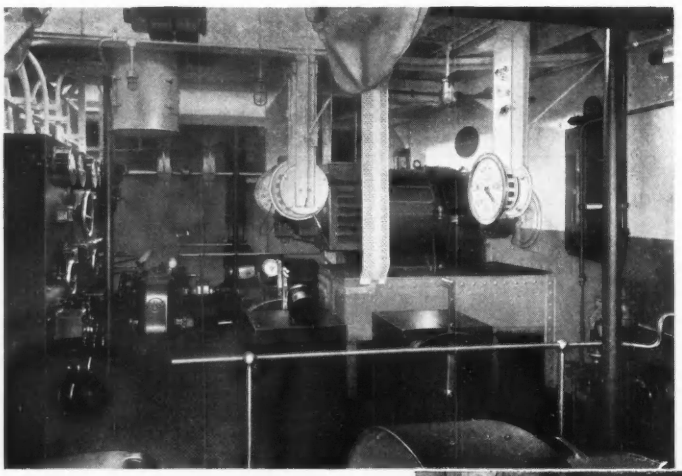


Fig. 2.—General view of the motor room showing one of the two 200 b.h.p. propulsion motors and reduction gearing, the 100 b.h.p. platform motor, controllers, propulsion cubicle and excitation panel.

As the vessel's carrying deck must be level with the quay at all stages of the tide, provision is made for raising and lowering the deck by means of six vertical screws operated through gearing by an electric motor.

PROPULSION EQUIPMENT.

The main propulsion equipment consists of two Diesel engines driving D.C. generators which supply power to the two propeller motors. On an extension of each generator shaft an exciter is carried for providing the current necessary for the separately excited fields of the generators and motors.

There are also two Diesel driven auxiliary generator sets for supplying the power required for lighting and for the engine-room auxiliaries.

Fig. 2 gives a general view of the motor room, showing one propulsion motor and gearing at the far side, the propulsion cubicle and excitation panel on the left, and, facing it, the platform motor and controllers.

The whole of this electrical equipment, together with the necessary control gear, was designed and manufactured by The General Electric Co. Ltd., the main and auxiliary Diesel engines being supplied by Davey Paxman & Co. (Colchester), Ltd.

MAIN ENGINES.

The main engines are six-cylinder, 4-stroke, solid injection Diesel units, 9½in. bore by 12in. stroke, rated to develop 250 b.h.p. continuously at 500 r.p.m. The design follows closely the lines of the standard Paxman heavy duty engine and embodies all its well-known features.

In order to secure adequate stiffness between engine and generator, tie bolts are provided which connect the top of the generator yoke to the bottom of the cylinder block thus virtually continuing the depth of the engine cylinder block right through to the generator end of the set. Figs. 2, 3 and 4 show the spacious engine and motor rooms resulting from the compact arrangement of machinery and bulkheads by the owners' Chief Mechanical Engineer.

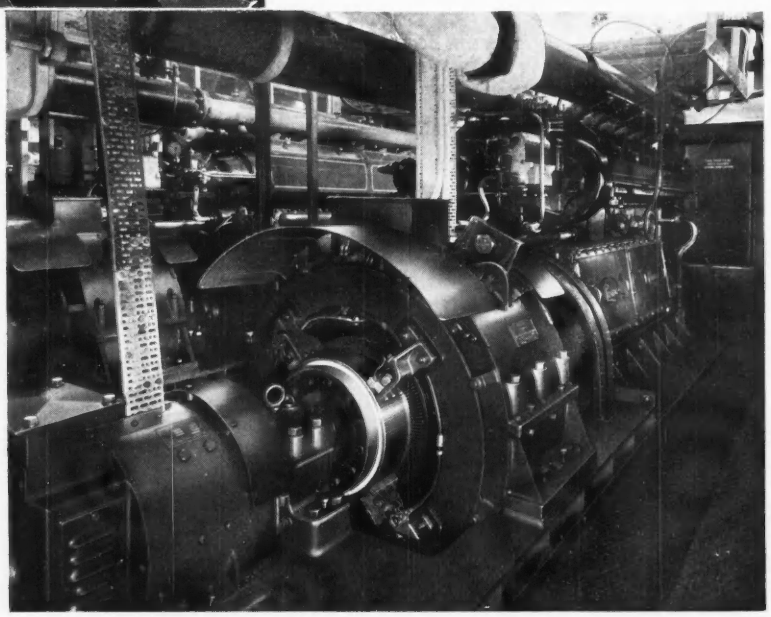


Fig. 3.—The engine room, showing the two main generating sets, each consisting of a 250 b.h.p. six-cylinder Diesel engine driving a 160 kW 440 volt, D.C. generator and exciter at 500 r.p.m.

MAIN GENERATORS.

Coupled to each of the main Diesel engines is a 160 kW 440 volt, D.C. generator running at a speed of 500 r.p.m. (fig. 3). In normal operation the generators run in parallel and are designed to give constant current at all voltages up to 440. For this purpose three separate field windings are provided,

namely, a self-excited shunt field, a series counter-compound winding, and a separately excited field which serves to provide the necessary excitation to enable the generators to give full load current at a very low voltage when starting up the motors.

The exciters run in tandem with the main generators (see fig. 3) and each is capable of supplying all the necessary excitation current for the separately excited fields of the generators, propulsion motors and platform motor. The exciters are not paralleled, only one of them being in service at a time.

AUXILIARY GENERATORS.

The auxiliary sets which are shown in fig. 4, consist of two six-cylinder, 4-stroke, solid injection Diesel engines developing 33 b.h.p. at 550 r.p.m., each directly coupled to a 25 kW 220 volt, generator. Either set is capable of supplying all the power necessary for lighting and auxiliaries.

Batteries are provided for emergency lighting and for use in the mornings before the auxiliary sets are started.

PROPULSION MOTORS AND PLATFORM MOTOR.

The two propulsion motors are of the forced ventilated protected type, each rated at 200 b.h.p. at 600 r.p.m. (fig. 5). These motors are provided with separately excited fields only. Each motor drives through a 4 : 1 reduction gear, two propellers, one at each end of a through shaft, at a speed of approximately 150 r.p.m. Four thrust blocks are provided for the two propeller shafts which are fitted with oil glands and sterntube lubrication.

For raising and lowering the vehicle platform a 100 h.p. 220 volt motor is installed having both self-excited and separately excited fields. This motor, which runs at a speed of 500 r.p.m., is coupled to a worm reduction gear which, in conjunction with the necessary bevel gearing, transmits the drive to a fore-and-aft shaft at each side of the vessel. By means of worm gears these in turn operate the six main vertical lifting screws—three at each side—upon which the platform is mounted, the total travel being 17ft., which adequately covers all conditions of the tide. Fig. 6 shows the platform motor and controller together with the two propulsion controllers.

OPERATION.

Since the operation of the ferry requires independent control of the speed and direction of rotation of both propulsion motors, irrespective of whether one or both generating sets are in operation, the constant current system of control has been adopted. Fig. 7 is a diagram of the main connections from which it will be seen that the propulsion motors are in series with each other and by varying the strength and reversing the polarity of each of the separately excited fields, the speed and direction of rotation of either motor can be varied over its entire range.

The platform motor is also operated on the constant current control system, and as it is not required to be used at

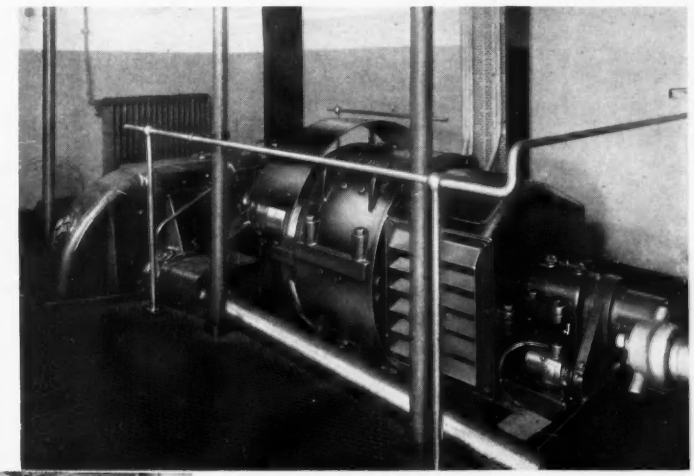


Fig. 5.—One of the two 200 b.h.p. main propulsion motors driving one pair of fore-and-aft propellers through a 4 : 1 reduction gear. The magneto machine actuating the speed indicator on the controller is seen mounted beside the right hand bearing.

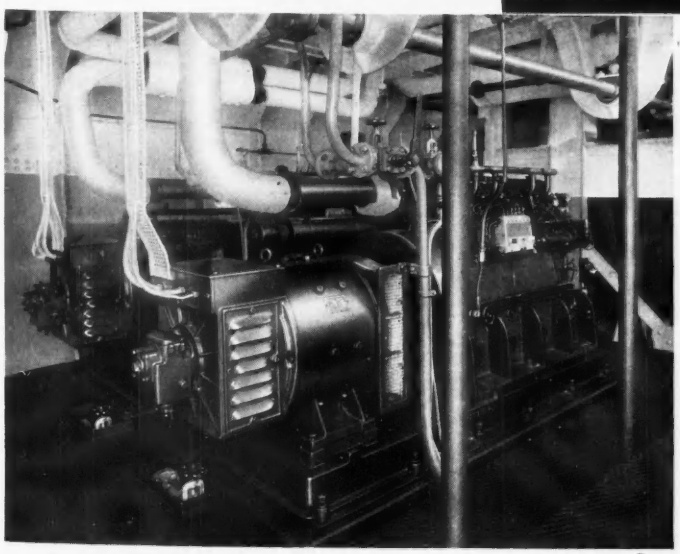


Fig. 4.—A view of the two auxiliary sets in the engine room, each comprising a 33 b.h.p. six-cylinder Diesel engine driving a 25 kW 220 volt, D.C. generator at 550 r.p.m.

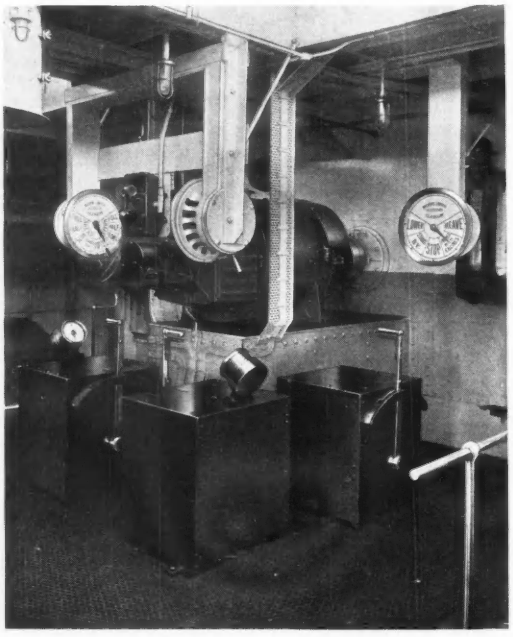


Fig. 6.—The 100 b.h.p. platform motor and controller together with the controllers and speed indicators for the two main propulsion motors.

the same time as the propulsion motors, a simple changeover switch is provided to change from propulsion to platform control.

Normally both generators will be running in parallel under all conditions of operation and in order to prevent excessive current in the platform motor the closing of the change-over switch automatically introduces limiting resistances into both shunt fields of the two generators. If for any reason only one generator is in service, the resistance for the other generator is not required and can be short circuited by auxiliary contacts.

In the interests of economy the engines are left idling while the vessel is being loaded or discharged at the quayside and for this reason it is not practicable to run the two exciters in parallel since they would become unstable at idling speed without load. Each exciter is therefore made large enough to handle the total excitation load and only one is in service at any given time.

A brief description of the manner of starting the ferry away from the quayside, which should be read in conjunction with fig. 8, showing the arrangement of the excitation and control circuits, will be helpful in explaining the essential features of the constant current method of control.

The selector switch is first moved into the propulsion position and the controllers all set at "stop." Both Diesel engines are then run up to full speed and the excitation circuit breaker closed. Current at very low voltage will now flow through the standing armatures of the two propulsion motors in series, but as the motor fields are not excited no movement takes place. The controllers are then moved in either the "ahead" or "astern" directions as required, thereby connecting the motor fields to the exciter, and the motors begin to rotate and run up to a speed corresponding to the position of the controller, the generator voltage building up at the same time to the value necessary to keep the current through the propulsion motors approximately constant.

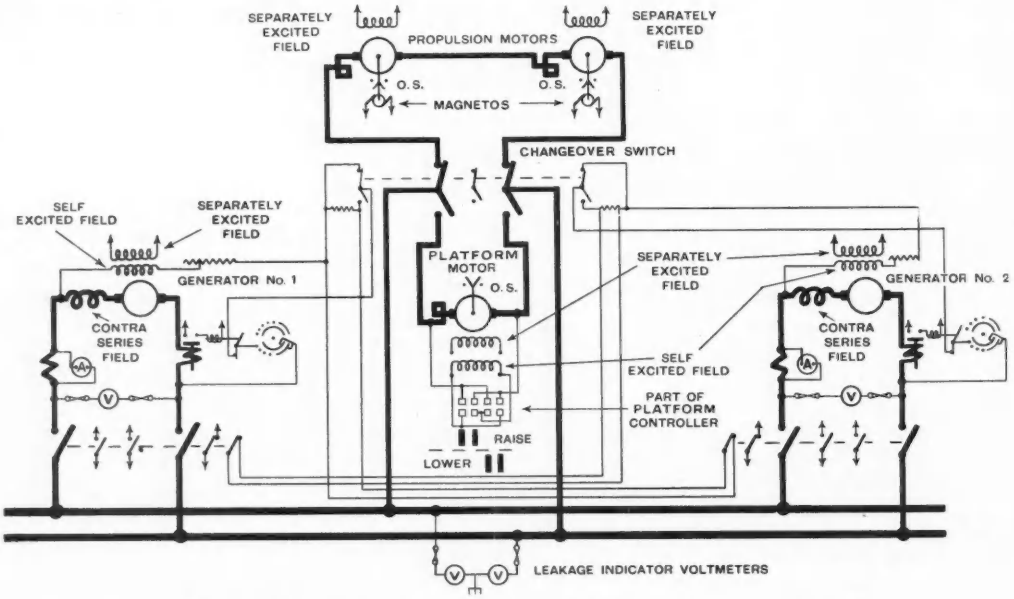


Fig. 7.—Diagram of main connections of the generators, propulsion motors and platform motor.

To stop the motors the controllers are returned to the "stop" position which removes the field excitation from both machines so that they slow down and come to a standstill. The current flowing from the generators remains practically constant but the voltage falls almost to zero. Should it be desired to stop the vessel more rapidly the controllers may be moved from the "stop" position towards full speed in the reverse direction as quickly as desired. This will bring the propellers to rest and start them rotating in the opposite direction in approximately $3\frac{1}{2}$ seconds, the current still remaining virtually constant, the voltage meanwhile dropping to zero and rising again as the motors reverse their direction of rotation. As the vessel loses way the controllers are finally restored to the "stop" position.

It will be noticed that in this system the motors are accelerated by strengthening the field, not by weakening it as in the more familiar case where the impressed voltage is kept constant.

CONTROL GEAR.

The control equipment includes a sheet steel cubicle of the "dead front" construction which houses the necessary switchgear, relays and instruments for the propulsion motors and the platform motor (fig. 9). Alongside this cubicle is a panel on which is mounted the control gear for the exciters. Four cam-operated contactor type controllers are provided for use with the propulsion motors, two

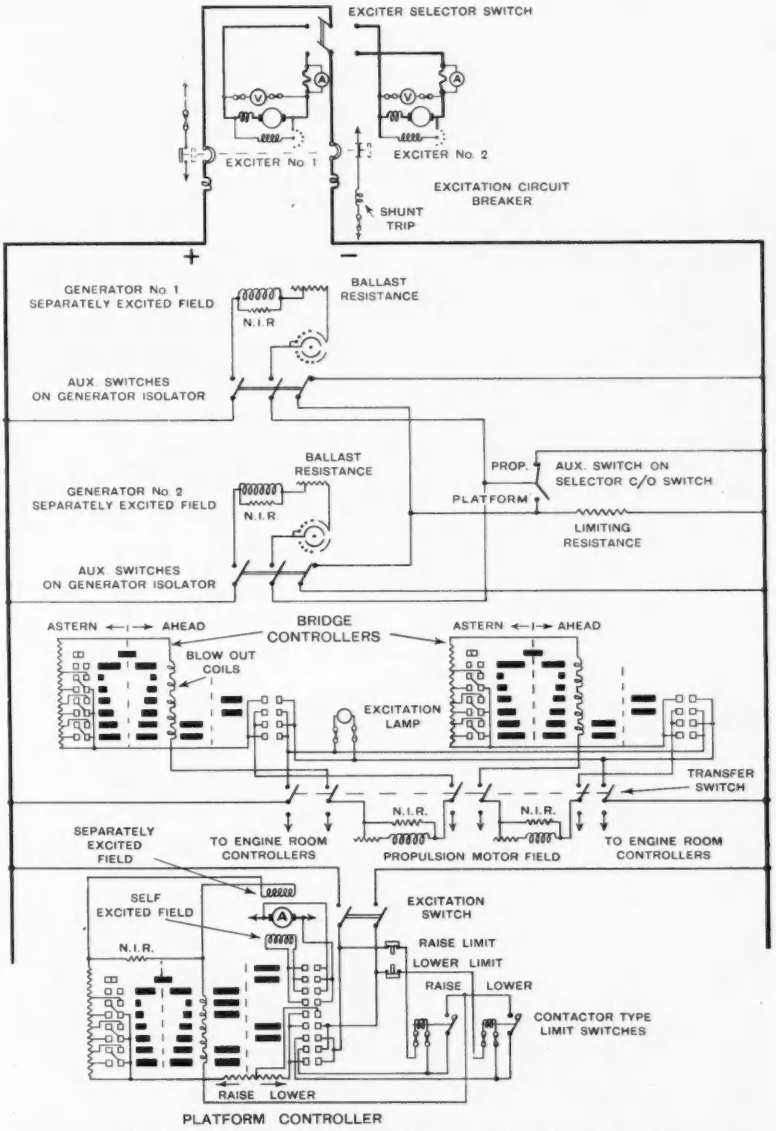


Fig. 8.—Diagram of excitation and controller circuits.

being mounted on the bridge as shown in fig. 10 and two in the engine room, so that the vessel can be controlled either directly from the bridge or

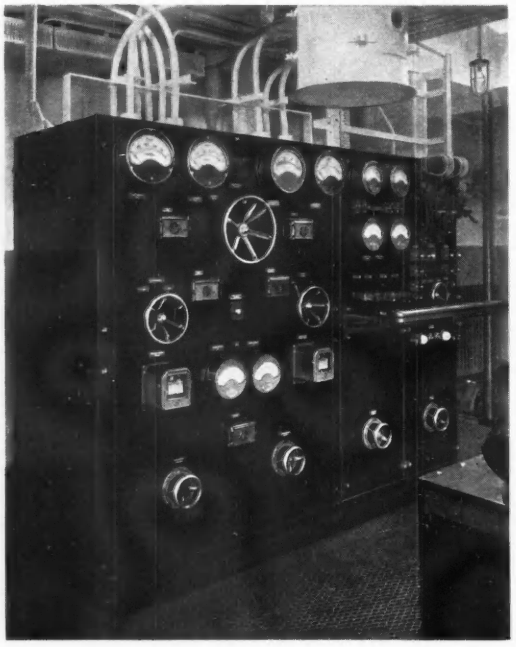


Fig. 9.—Propulsion cubicle and exciter panel.

from the engine room in accordance with the usual ship telegraph signals. Each controller carries a propeller speed indicator operated from magneto machines driven from the shafts of the propulsion motors. The controller for the platform motor is situated in the engine room (fig. 6) and is always operated in response to signals received from the bridge. Limit switches are fitted both top and bottom as a safeguard against the platform's over-travelling.

To provide against the remote contingency of stripped gears or broken couplings, which would result in throwing the load entirely off an excited motor and hence in dangerous overspeeding, every motor is fitted with an overspeed device which on operation trips the excitation circuit breaker, thereby removing all power both from the motors and generators.

RIVER TRIALS.

Official trials of the ferry were carried out in the King George V Dock at Glasgow on April 13th, when the performance of the vessel and her machinery proved in every way satisfactory. The propulsion motors had an ample reserve of power and, with the vessel on a straight course, would have been capable of propelling her at about twice the normal running speed required in service. The extra power, however, is needed to obtain quick response in manœuvring, which is essential in the conditions in which the ferry is employed. The method of bridge control has worked throughout to the entire satisfaction of the Captains, enabling them to shorten the duration of the trip cycles.

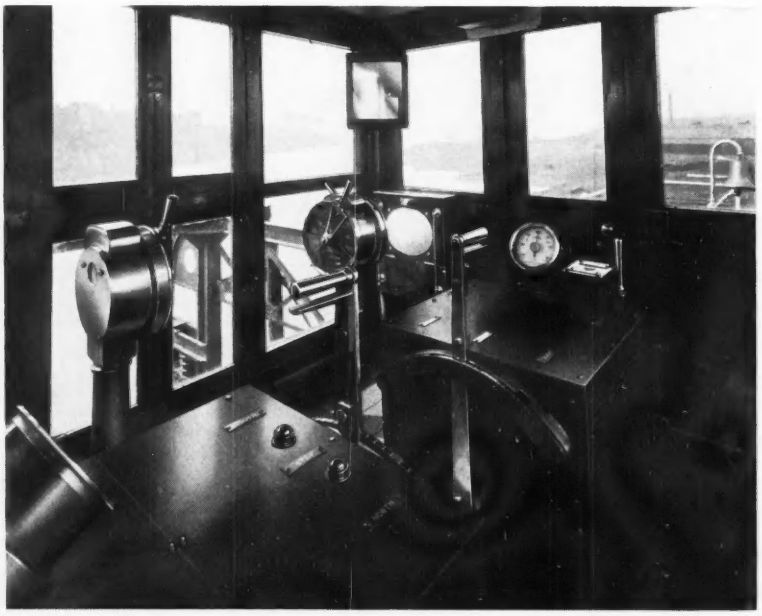


Fig. 10.—View of the upper deck control cabin showing the two propulsion motor controllers with their speed indicators and the engine-room telegraph.

Technical Literature.

A DIGEST OF RECENT BOOKS, ARTICLES AND PAPERS BY MEMBERS OF THE STAFF OF THE G.E.C. AND ITS ASSOCIATED COMPANIES.

ALTERNATOR REACTANCES.

By C. J. O. Garrard (Witton Engineering Works).

The Electrician, p. 149, 5th August, 1938.

The definition of the reactance of an alternator is important for the calculation of short circuit currents in networks. The article describes the phenomena that take place when an alternator is short circuited and derives therefrom definitions of a number of the quantities commonly known as reactance, such as "leakage reactance," "transient reactance," "subtransient reactance," and so on. It is shown that for most calculations in connection with switchgear, knowledge of the reactance due to the stator leakage flux is sufficient.

GASES AND METALS.

By C. J. Smithells (G.E.C. Research Laboratories).

J. Royal Soc. Arts. (Cantor Lecture), Vol. 86, August 5th, 12th and 19th, 1938.

The subject is divided into three processes—the adsorption of gases on metal surfaces, the diffusion of gases through solid metals and the solution of gases in metals. It is shown, however, that the phenomena of adsorption, diffusion and solution are closely related and that the results of research on apparently quite unrelated phenomena can be co-ordinated.

LUMINESCENT MATERIALS AND THEIR APPLICATION TO LIGHT SOURCES.*

By J. W. Ryde (G.E.C. Research Laboratories).

Trans. Illum. Eng. Soc. (London) 3, p. 114, August 1938.

An historical review is given of materials with luminescent properties and the mechanics of their excitation. Their application to the colour modification and the increase of efficiency of light sources is described in detail.

A FORM OF DISTORTION KNOWN AS THE "BUZZ EFFECT."*

By K. A. Macfadyen (M.O. Valve Co. and the G.E.C. Research Laboratories).

Wireless Engineer, XV., 310, June 1938.

A description of a kind of distortion found in certain samples of the high-slope output pentode is given. The mechanism of the effect is explained and the theory employed to account for radio-interference effects in certain vacuum lamp circuits. Reference is made to earlier papers on the same subject.

SECONDARY-ELECTRON EMISSION OF NICKEL, COBALT AND IRON AS A FUNCTION OF TEMPERATURE*.

By L. R. G. Treloar and D. H. Landon (M.O. Valve Co. and the G.E.C. Research Laboratories).

Proc. Phys. Soc. 50, 625, 1st Sept., 1938.

To investigate the evidence of other workers that the magnetic and structural changes which occur in ferromagnetic metals are accompanied by changes in the secondary-electron emission, the coefficient of this emission has been measured for nickel, cobalt and iron at various primary voltages up to a temperature of about 400° C. Only slight and gradual changes were found.

THE COLORIMETRIC DETERMINATION OF SMALL QUANTITIES OF IRON OXIDE IN GLASS AND GLASS SAND.*

By R. C. Chirnside (G.E.C. Research Laboratories).

Jour. Society of Glass Technology, XXII., 41, 1938.

The use of thioglycollic acid is suggested in place of thiocyanate for the colorimetric determination of iron. A description of experience in the use of this new reagent is given. The reagent is found to be free from most of the errors pertaining to the use of thiocyanate.

THERMIONIC EMISSION FROM CARBON.*

By A. L. Reimann (M.O. Valve Co. and the G.E.C. Research Laboratories).

Proc. Phys. Soc. 50, p. 496, July 1st, 1938.

The thermionic emission from clean carbon was measured at a series of temperatures between 1665° and 2191°K and with different applied fields at each temperature.

THE EVAPORATION OF ATOMS, IONS AND ELECTRONS FROM TUNGSTEN.*

By A. L. Reimann (The M.O. Valve Co. and the G.E.C. Research Laboratories).

Phil. Mag. 25, 834, June, 1938.

Measurements were carried out in the evaporation of atoms, ions and electrons. As with previous investigations the agreement between theory and experiment is not very close and it is suggested that there must be some other variable surface condition of which account should be taken in the theory.

OXIDE COATED CATHODES I. PARTICLE SIZE AND THERMIONIC EMISSION.*

By M. Benjamin, R. L. Huck and R. O. Jenkins (The M.O. Valve Co. and the G.E.C. Research Laboratories).

Proc. Phys. Soc. 50, p. 345, May, 1938.

An investigation showing that only the particles forming the surface of oxide coated cathodes emit. Smaller particles give greater and more uniform emission. The size of the oxide particles is determined by the method of preparation of the carbonates. A theory is advanced to explain why only the outermost surface particles emit.

SINTERED ALLOYS I. COPPER-NICKEL-TUNGSTEN ALLOYS SINTERED WITH A LIQUID PHASE PRESENT.*

By G. H. S. Price, C. J. Smithells and S. V. Williams (G.E.C. Research Laboratories).

Jour. Inst. Metals, LXII, No. 1, 1938.

Factors which influence the preparation of alloys made by mixing, pressing and sintering metal powders in an atmosphere of hydrogen have been investigated with particular reference to the copper-nickel-tungsten system. The distinctive character of the work is that sintering has been carried out at temperatures sufficiently high to ensure the presence of a liquid phase during the formation of the alloy.

LOUD SPEAKER REPRODUCTION OF CONTINUOUS-SPECTRUM INPUT.*

By F. H. Brittain and E. Williams (G.E.C. Research Laboratories).

Wireless Engineer XV, p. 16, Jan. 1938.

A new method of testing loud speakers is described. Instead of the usual pure sine wave electrical input to the loud speaker an input containing all frequencies simultaneously is used. A comparison is made of the response curves obtained with this new method and with the orthodox method.

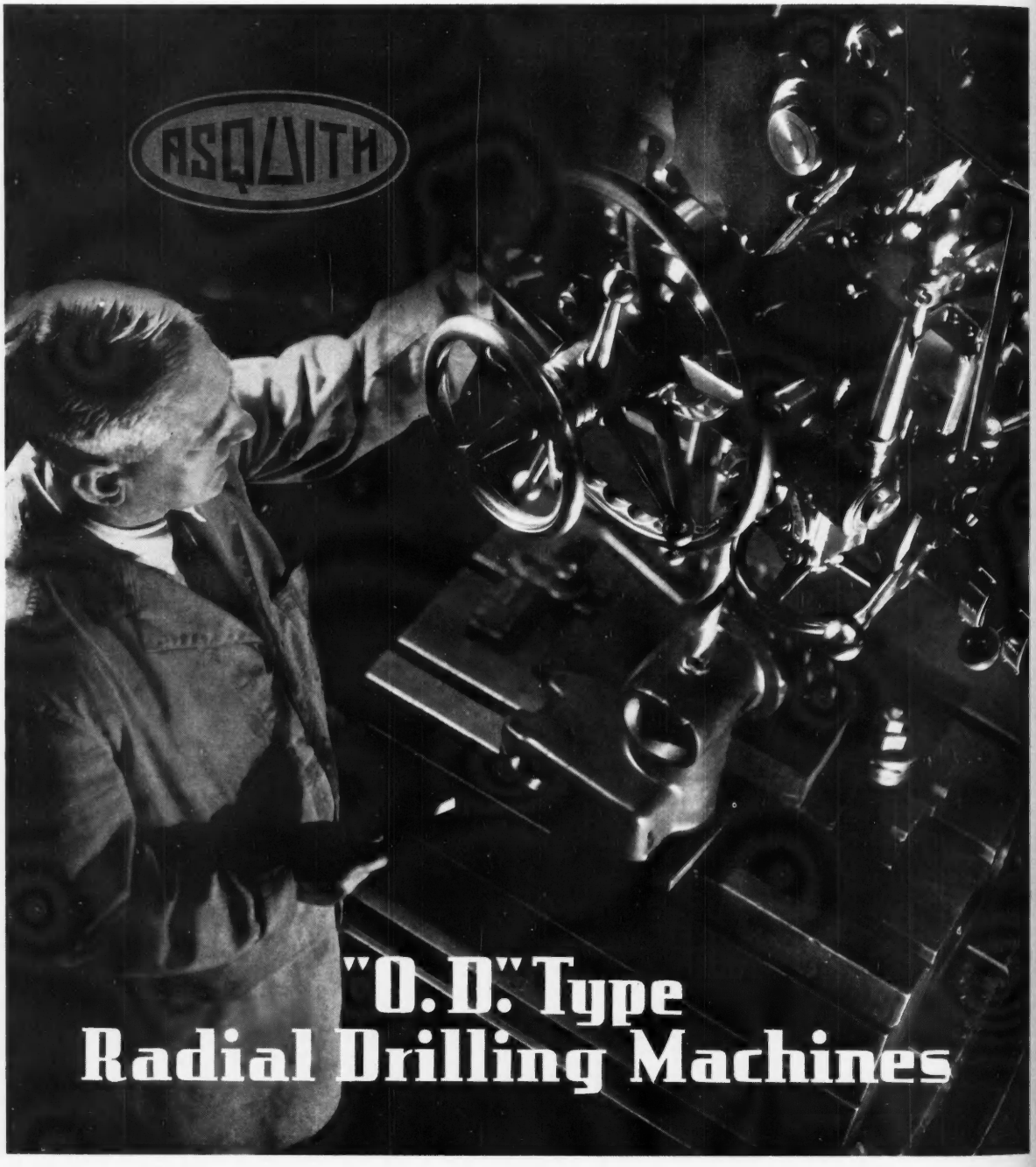
THE ELECTRIC LOCOMOTIVE AS A VEHICLE.

By E. H. Croft (Witton Engineering Works).

Railway Gazette Supplement, 22nd July, 1938.

The dynamics of the movement of a locomotive running over an irregular track are briefly discussed. Certain improvements in the riding qualities are suggested and it is shown that in certain instances a high centre of gravity is desirable and in others a low centre of gravity. Some suggestions are made whereby a low centre of gravity can be adopted without detriment to the riding qualities.

***A limited number of reprints is available ; copies may be obtained on application to the Editor, G.E.C. Journal, Witton Engineering Works, B'ham, 6.**



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IN THIS ISSUE.

ELECTRICAL PROGRESS AND DEVELOPMENT DURING 1937

SOME FACTORS GOVERNING THE DESIGN OF MULTICHANNEL CARRIER TELEPHONE SYSTEMS FOR UNDERGROUND CABLES

THE APPRAISEMENT OF LIGHTING

THE DESIGN OF DOMESTIC ELECTRIC COOKERS

Vol. IX., No. 1. *February, 1938.*

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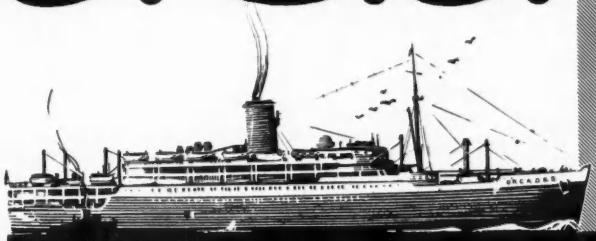

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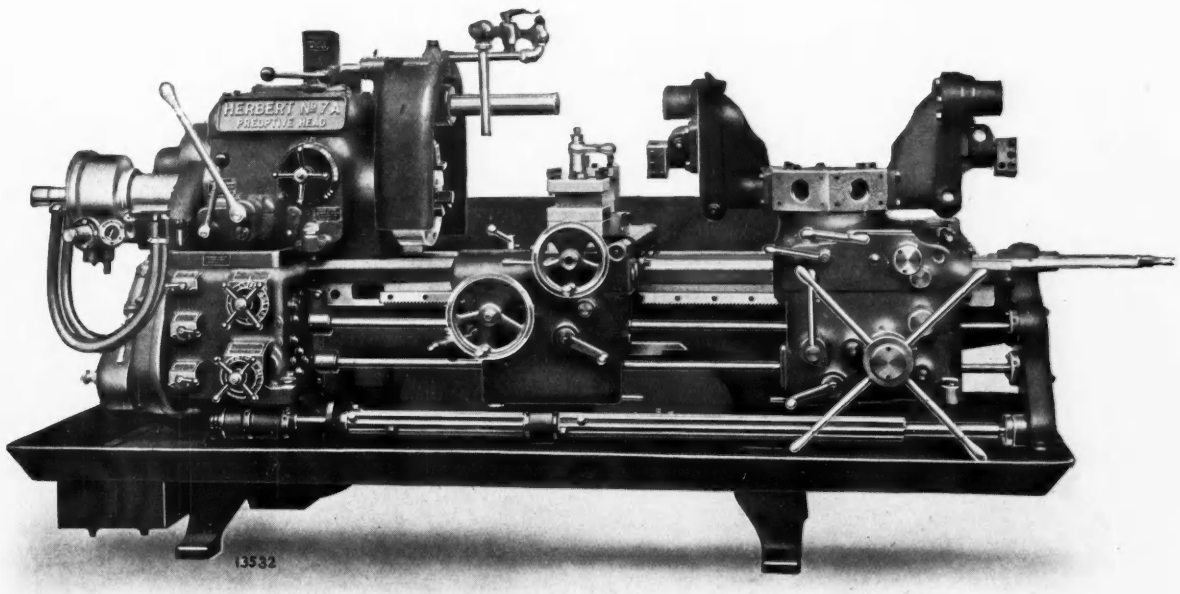

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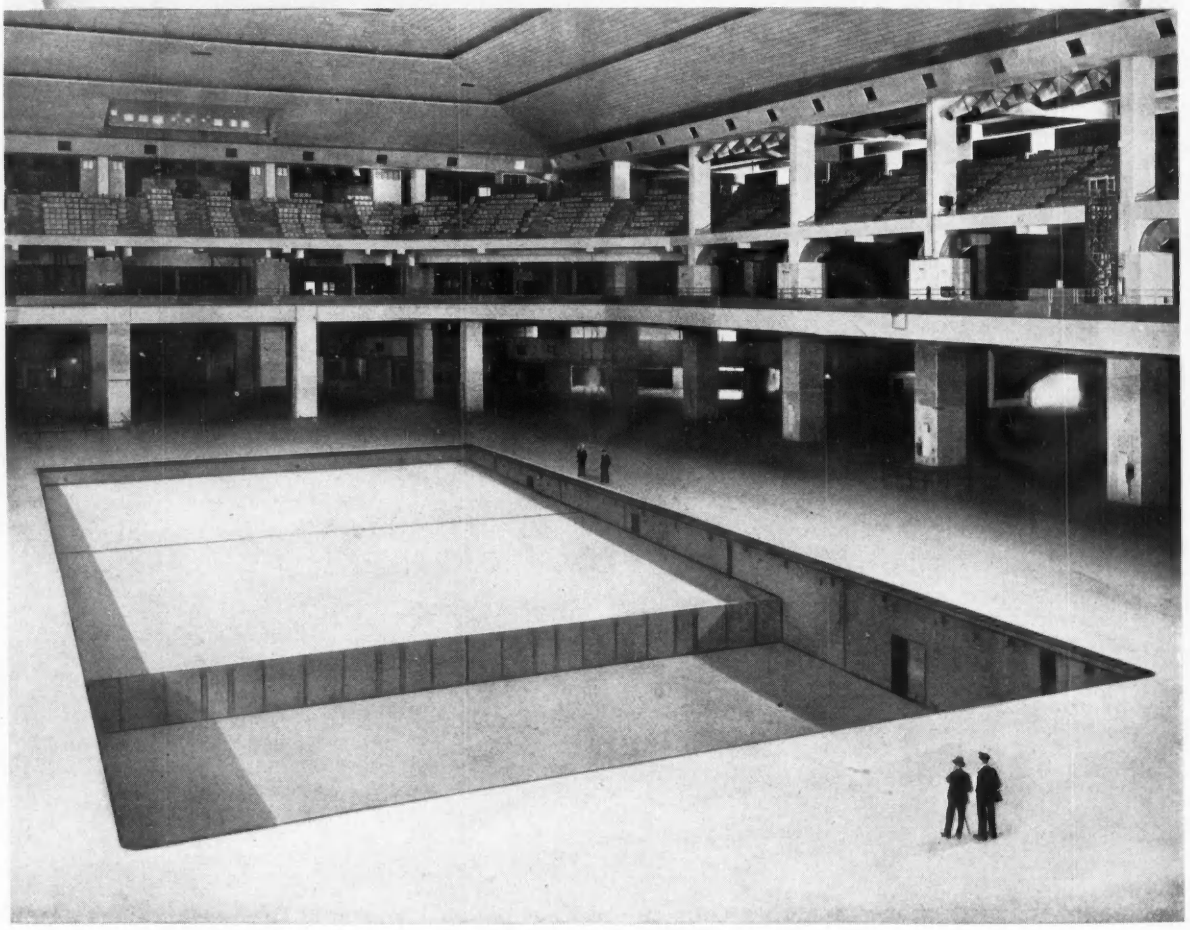

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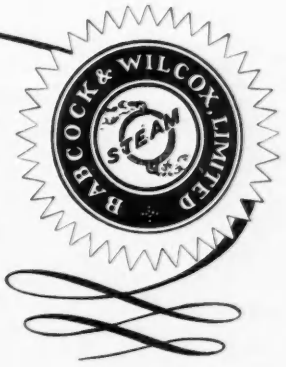

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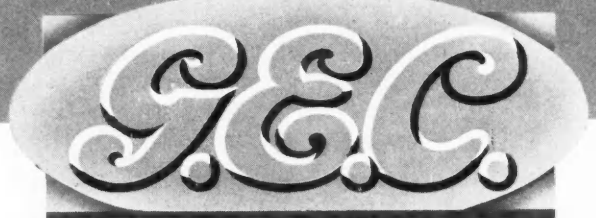

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RECENT PROGRESS IN POWER RECTIFIERS AND THEIR APPLICATIONS.

THE UNIT SECTIONAL DRIVE OF A LARGE PAPER MACHINE.

THE INSTALLATION OF ELECTRICAL APPARATUS IN HAZARDOUS SITUATIONS.

SWITCHGEAR EXTENSIONS AT THORPE POWER STATION, NORWICH.

THE DESIGN OF DOMESTIC ELECTRIC COOKERS.

THE CONCENTRATION OF MINERALS BY FLOTATION.

LIGHTING IN SHOPS AND STORES.

COAL HANDLING PLANT ON THE LUNGHAI RAILWAY.

TECHNICAL LITERATURE.

Vol. IX., No. 2. *May*, 1938.

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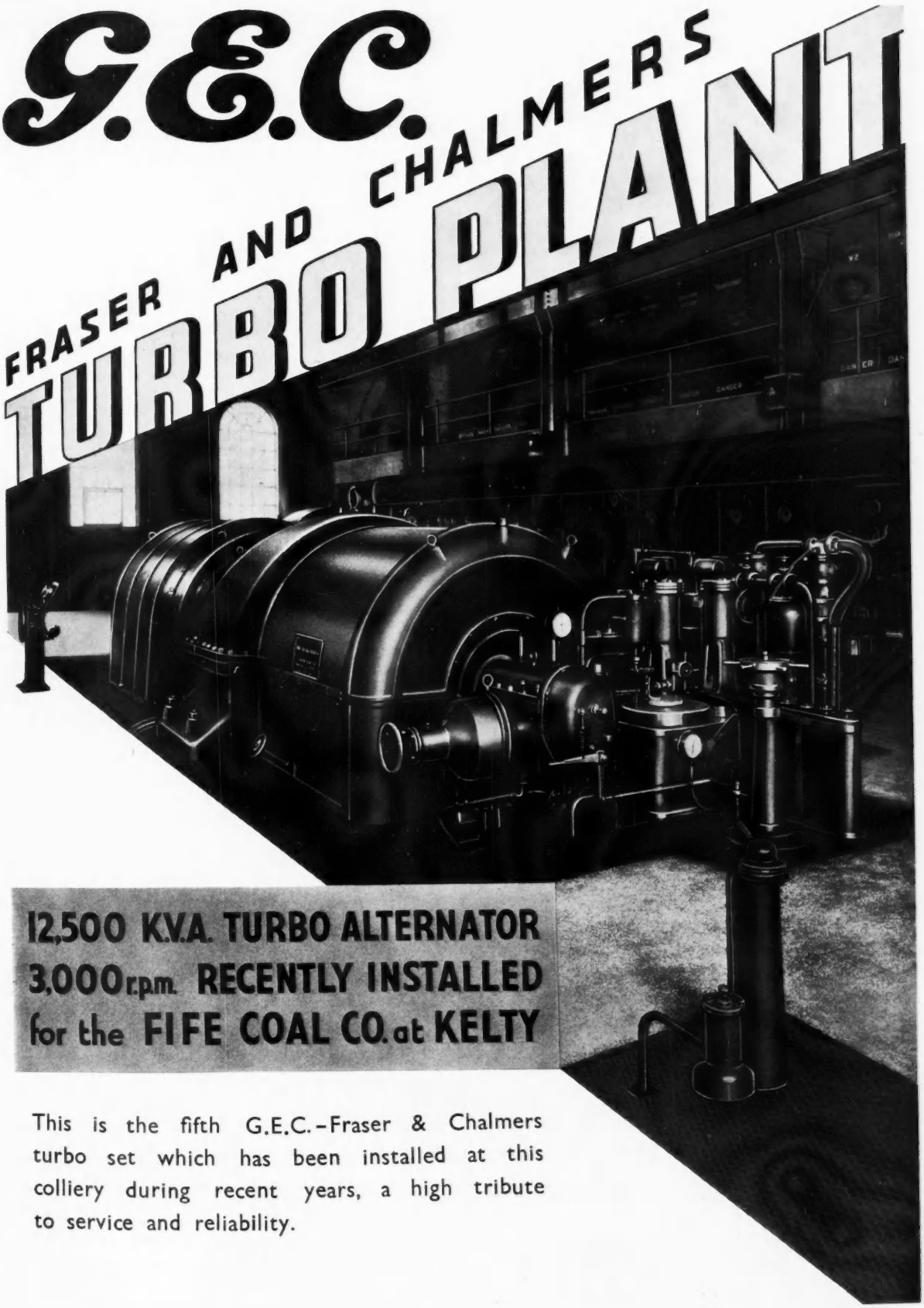

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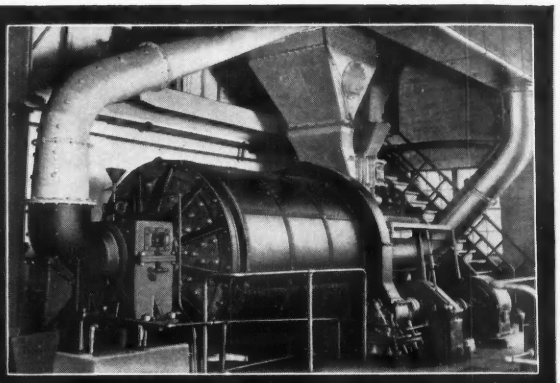

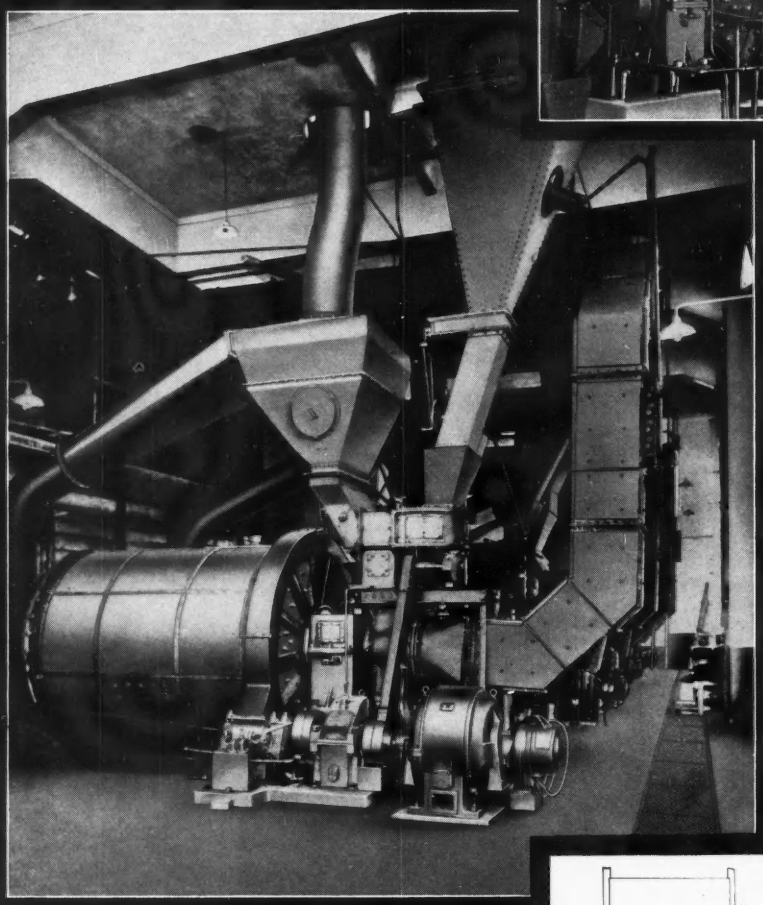

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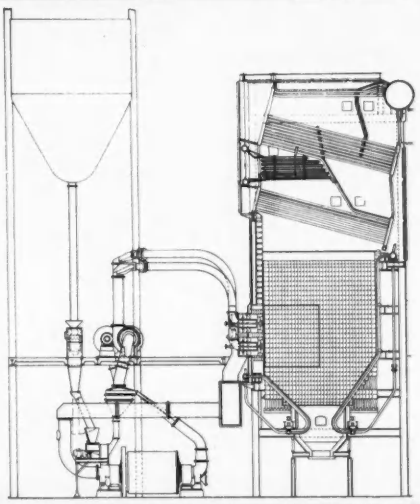

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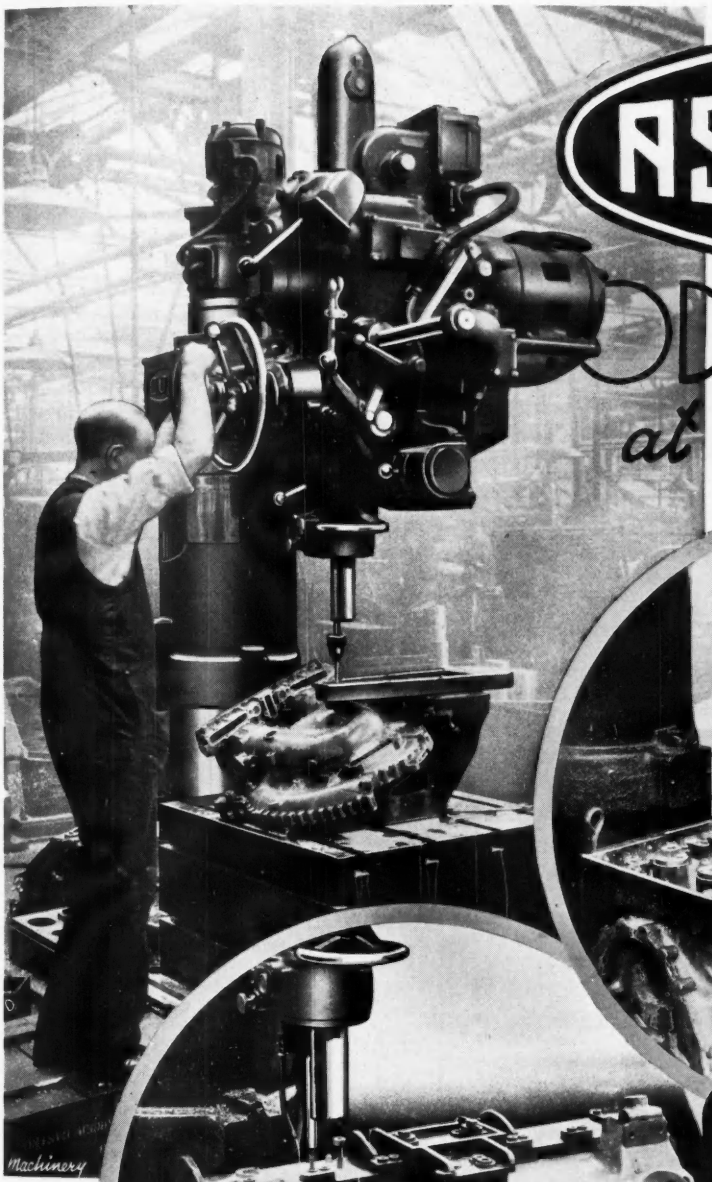

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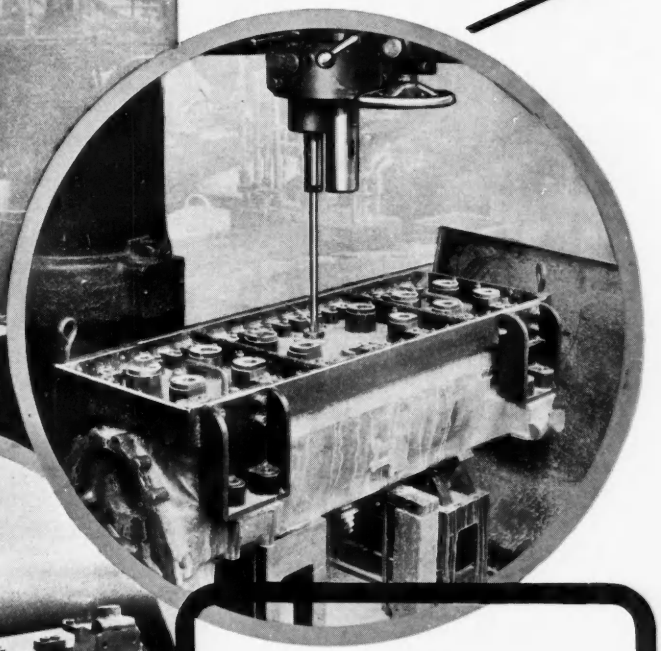

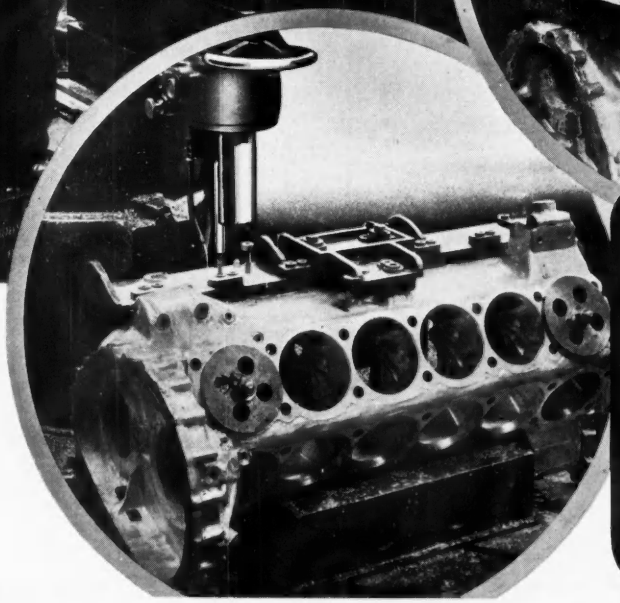

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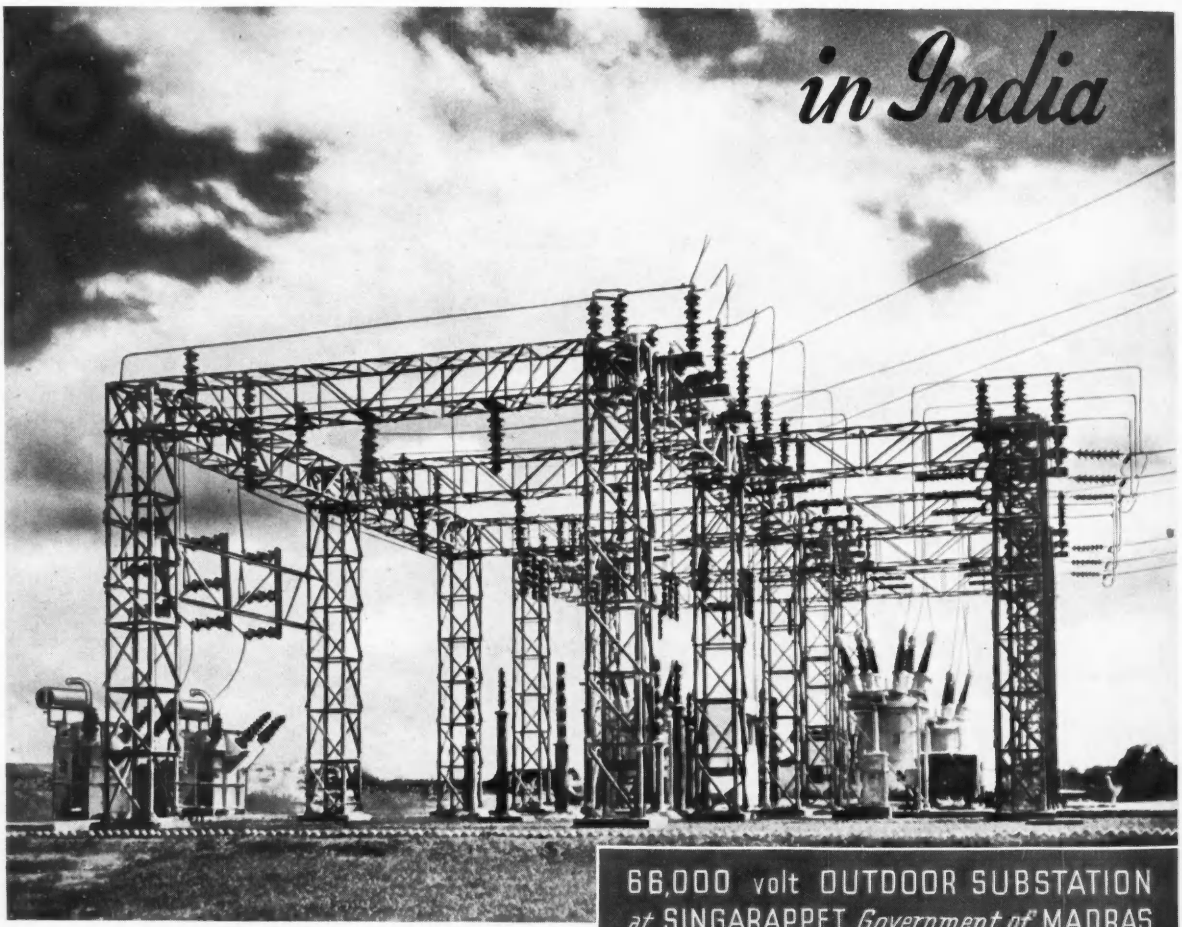

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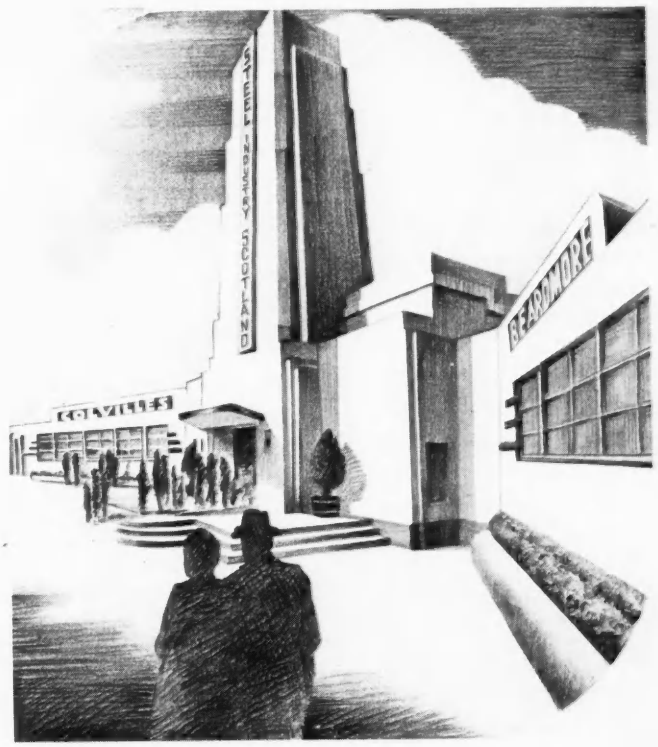

An artist's impression of "Steel Industry Scotland" Pavilion at the Empire Exhibition, Bellahouston Park, Glasgow, wherein will be displayed the Exhibits of
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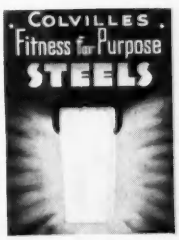

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Fan Works Witton, Birmingham
Moulded Insulation Works Witton, Birmingham
Telephone Works Coventry
Wireless Apparatus Works Coventry
Valve Works Hammersmith, London
Instrument Works Salford
Lamp Works Hammersmith, London and Wembley, Middlesex
Accessories Works Union Works, Wembley, Middlesex
Glass Works Lemington-on-Tyne and Wembley
Meter Works Birmingham
Steam-Turbine Works Erith
Conveying and Mining Plant Works Erith
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G.E.C. Journal

Bureau of Standards
AUG 24 1938

IN THIS ISSUE.

FLUORESCENT TUBE LIGHTING.

HIGH POWER VALVES CONSTRUCTION, TESTING AND OPERATION—PART I.

REVIEW OF THE REPORT OF THE MINISTRY OF TRANSPORT DEPARTMENTAL COMMITTEE ON STREET LIGHTING.

MULTI-CHANNEL CARRIER TELEPHONE CABLE.

RECENT PROGRESS IN POWER RECTIFIERS AND THEIR APPLICATIONS PART II.

CONCENTRATION OF MINERALS BY FLOTATION—PART II.

LOW TEMPERATURE WARMING SYSTEMS.

Vol. IX., No. 3. *August, 1938.*

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THE LARGEST BRITISH ELECTRICAL MANUFACTURING ORGANISATION IN THE EMPIRE

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PIONEERS IN EVERY PHASE OF ELECTRICAL DEVELOPMENT

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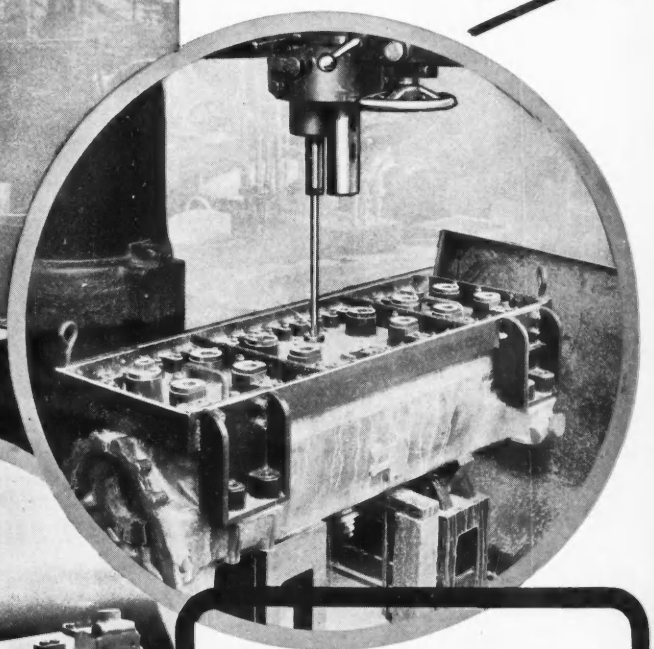
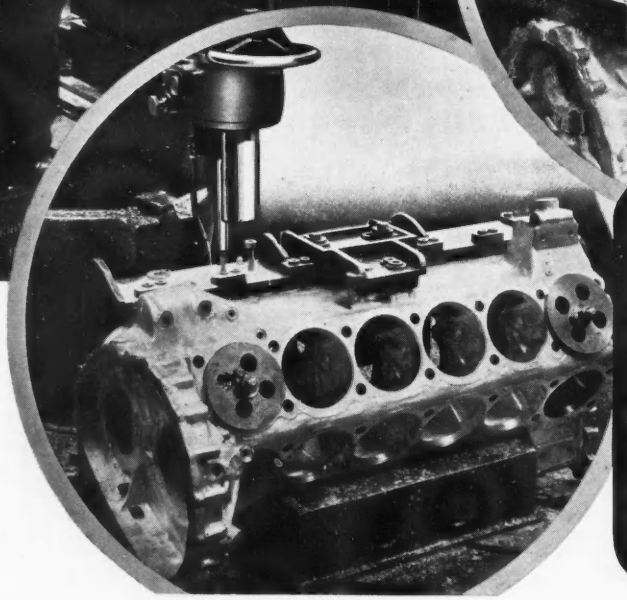
at Rolls Royce





Asquith radials are kept busily employed at Rolls Royce Ltd., Derby. Many of our machines are installed here, including 15 "O.D." type radial drills, and our photographs show typical operations on crankcase and supercharger castings for the well-known MERLIN aero. engine.
There are Asquith drilling machines for all classes of work. Ask for Asquith production figures on your own jobs.

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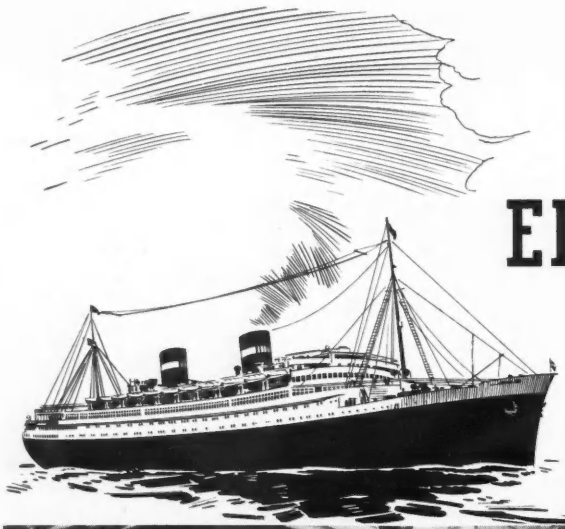
PUMPLESS AIR-COOLED STEELCLAD MERCURY ARC RECTIFIERS

ADOPTED THROUGHOUT THE WORLD FOR TRACTION, MUNICIPAL AND INDUSTRIAL SERVICES

One of the 250 kW 600 volt D.C. pumpless air-cooled steelclad mercury arc rectifier equipments installed for St. Helens Corporation, Lancashire.



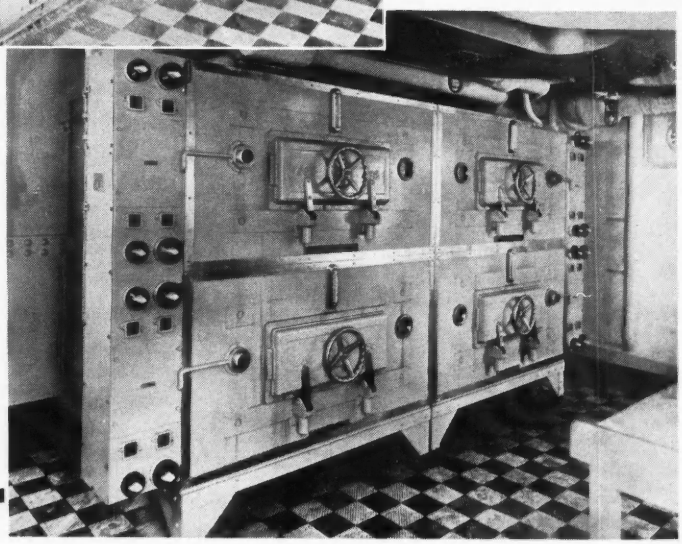
G.E.C.

ELECTRIC GALLEY EQUIPMENT

IN THE

"NIEUW AMSTERDAM"

— THE LATEST VESSEL OF THE HOLLAND-AMERICA LINE



G.E.C. electric galley equipment is installed throughout this new ship.

These two views show, right, the breadbaking ovens in the ship's bakery, and above, an eight oven range in the first class galley.

A similar eight oven range is included in the equipment for the tourist class galley.

G.E.C. luminous silent call system is also used throughout.

G.E.C.

33 kV METAL-CLAD SWITCHGEAR

33 kV, 500,000 kVA Metalclad switchboard in the Shifnal substation of the West Midland Joint Electricity Authority.

THIS GEAR HAS BEEN FULLY TESTED IN THE G.E.C. HIGH POWER TEST LABORATORY

G.E.C.
ELECTRIC FURNACES

The three furnaces illustrated include (1) a complete Grunewald plant for the bright annealing of strip in coils. (2) a batch type furnace complete with charging machine and fans to ensure quick and uniform heating of charge. (3) a similar furnace of larger capacity.

THE THIRD G.E.C. FURNACE AT THE WORKS OF J. F. RATCLIFF (METALS) LTD. FOR THE ANNEALING OF THEIR FAMOUS "LUSTER" METALS

Gashing the slots in scroll jaws. Slots are .100" wide by .215" deep, limit on the depth being—.001".

MILLING CHUCK COMPONENTS

AT THE WORKS OF MESSRS. F. PRATT & Co. Ltd., HALIFAX

Messrs. F. Pratt & Co. Ltd., the well-known makers of Lathe Chucks, use ten Herbert No. 33 Plain Milling Machines for milling chuck components.

Cuts are comparatively heavy; materials are hard and include both case-hardening mild steel and chrome veradium steel of 60/70 tons tensile.

The exceptional rigidity of the machines ensures an excellent finish and a high degree of accuracy in the work.

Messrs. Pratt & Co. Ltd., inform us that the machines have given complete satisfaction.

CAPACITY: 21 × 6′ × 16″

Roller-bearing spindle and ball and roller-bearings to all shafts in driving and feed boxes.

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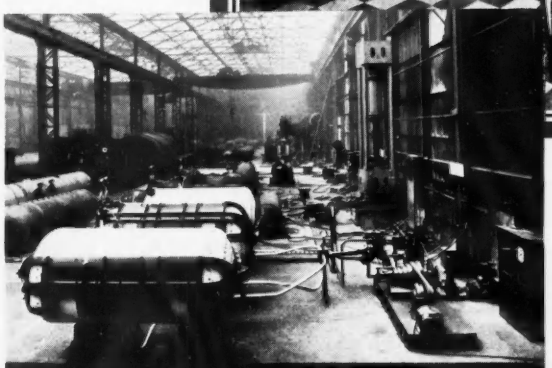
BABCOCK RESEARCH

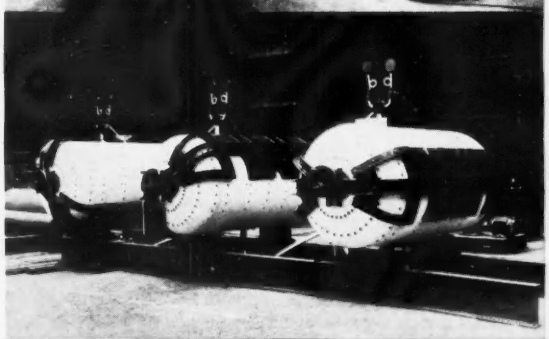
(RESEARCH ADVERTISEMENT No. 1)

The importance which Babcock & Wilcox Limited attach to the value of Research Work is expressed in the extent and equipment of their Laboratories at Renfrew.

The progress in steam generation demands continuous investigation into the physical and mechanical properties of materials combined with exploratory Research Work on new methods and conception.

THE BABCOCK RENFREW LABORATORIES ARE FULLY EQUIPPED FOR THIS WORK.





IN order to give some indication of the scope and extent of the Research Work undertaken at Renfrew it is proposed to publish a series of illustrations of which these are first examples.

They illustrate the explorative fatigue testing of Babcock Class I Fusion Welded drums for high pressures under stress reversals ranging from zero to 1,100 lbs./sq. in. applied in cycles of six reversals per minute.

The top picture shows details of the equipment used for obtaining micrometer measurements of distortion under stress. The two bottom pictures show three drums of different plate thickness undergoing fatigue tests, together with the hydraulic gear used for testing. The centre illustrates a section of the Mechanical Laboratory engaged on detailed testing incidental to this work.

This Research Test is representative of one of the many links of the chain which Babcock & Wilcox have forged to combine high efficiency with reliability in service.

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Witton, Birmingham
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Witton, Birmingham
Moulded Insulation Works
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Radio Works
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Steam-Turbine Works
Erith
Conveying and Mining Plant Works—Erith
Cable Works
Southampton and Eastleigh
Heating and Cooking Apparatus Works
Magnet Works, Birmingham
Electric Light Fittings Works
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G.E.C. Journal

IN THIS ISSUE.

THE ECONOMICS OF VERY HIGH POWER TRANSMISSION OVER LONG DISTANCES.

ILLUMINATION AT THE EMPIRE EXHIBITION, SCOTLAND, 1938.

THE ELECTRIFICATION OF JARROW TUBE WORKS.

HIGH-POWER VALVES: CONSTRUCTION, TESTING AND OPERATION—PART II.

SIGNALLING AT WAVERLEY STATION, L.N.E.R., EDINBURGH.

CURRENT LIMITING REACTORS.

THE CONCENTRATION OF MINERALS BY FLOTATION—PART III.

DIESEL-ELECTRIC FERRY FOR THE CLYDE.

TECHNICAL LITERATURE.

Vol. IX., No. 4. *November, 1938.*

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G.E.C. LIGHTING at MANCHESTER CITY HALL EXTENSIONS

This view of the electricity showrooms typifies the high standard of illumination which is achieved throughout the new building.

Nearly 2,000 G.E.C. lighting fittings as well as 4,000 feet of OSIRA fluorescent tubing and a large number of OSRAM Lamps are used in the principal rooms, the offices, corridors and staircases.

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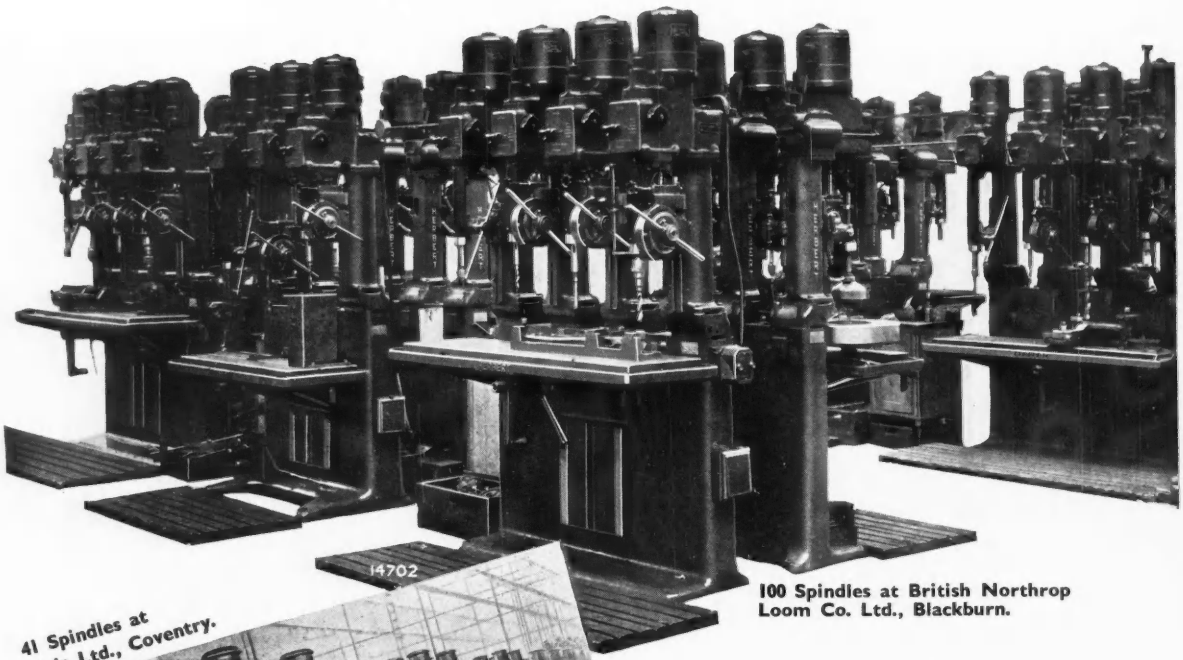
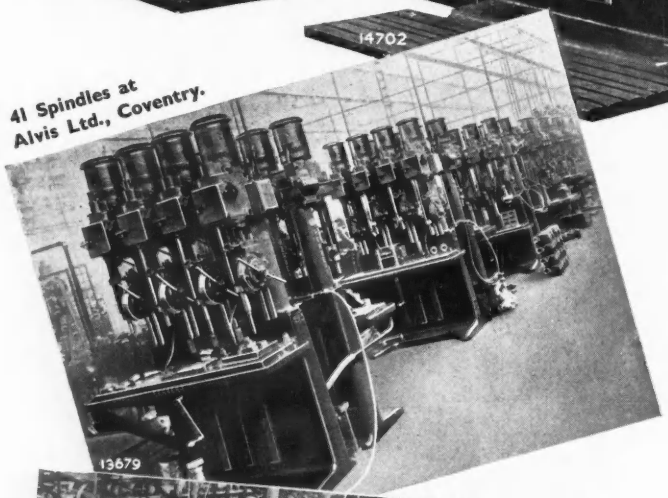
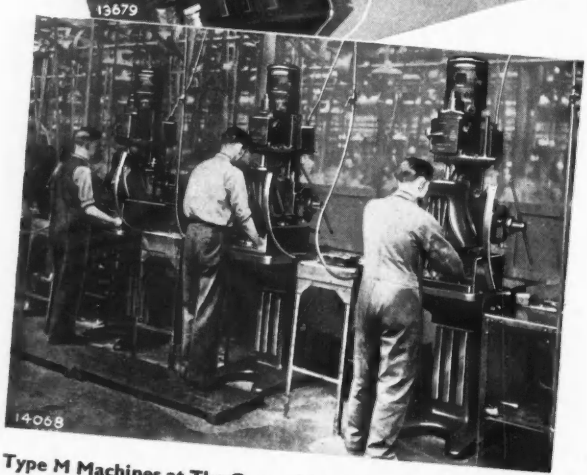


100 Spindles at British Northrop Loom Co. Ltd., Blackburn.

41 Spindles at Alvis Ltd., Coventry.





Type M Machines at The General Electric Co. Ltd., Coventry.

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FOR DRILLING AND TAPPING FROM THE SMALLEST HOLES UP TO $1\frac{1}{4}$".

FOR GENERAL WORK OR HIGH PRODUCTION, SINGLE OR MULTI-SPINDLE ; SPEEDS UP TO 18,000 r.p.m.

COLUMN OR BENCH WITH 1, 2, 3, 4 or 6 SPINDLES.

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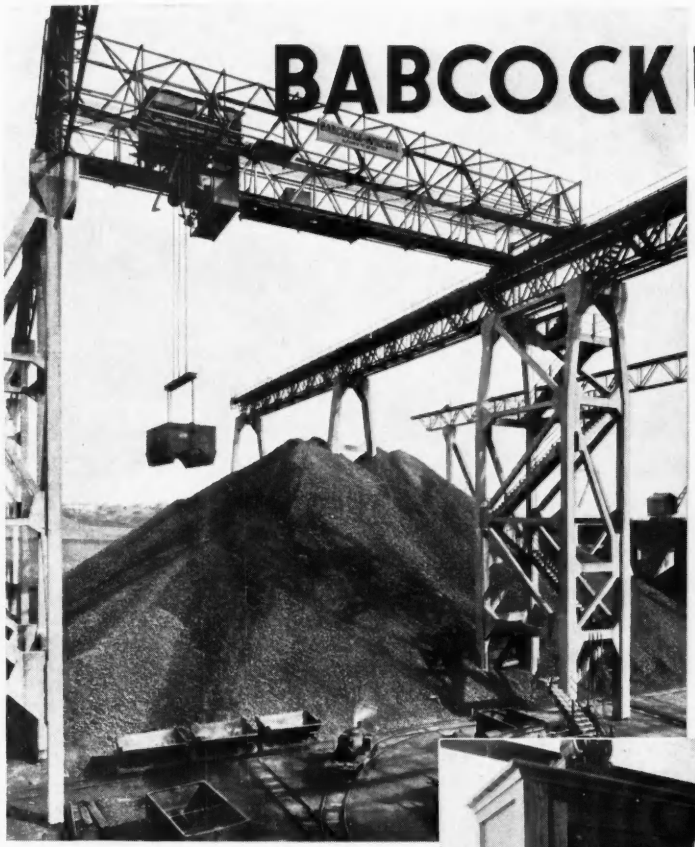


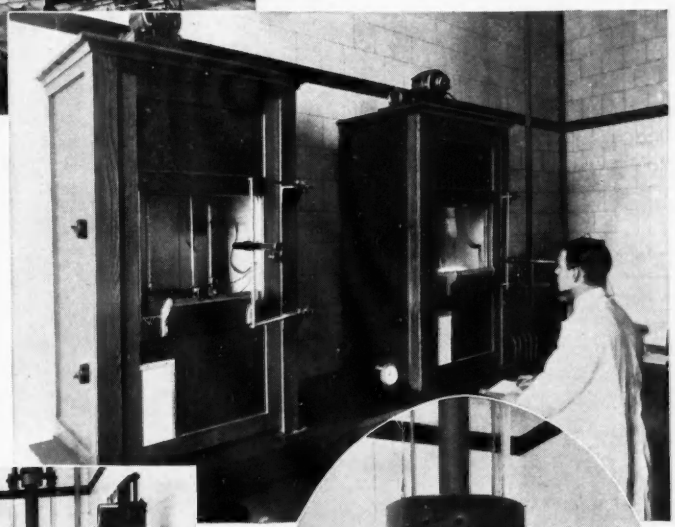
BABCOCK RESEARCH

(RESEARCH ADVERTISEMENT NO. 2.)

THE maintenance of a high standard of combustion efficiency and the design of steam generating plants capable of long periods of continuous service are largely dependent on the accurate determination of the fundamental properties of a wide variety of fuels from all parts of the World.

The FUEL SECTION of the BABCOCK RESEARCH LABORATORIES is elaborately equipped for this work and includes special apparatus which has been developed and built by the Research Department.

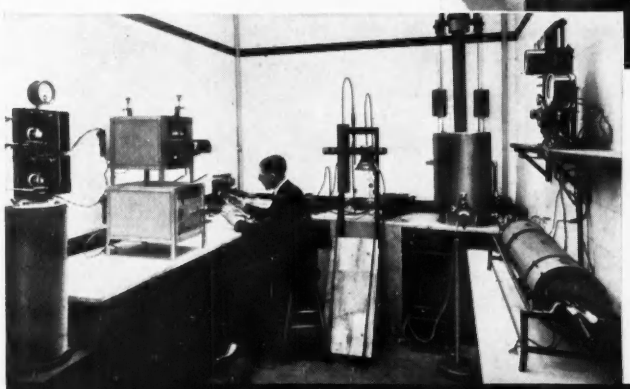
These investigations cover a wide field and include the determination of moisture contents, carbon and hydrogen contents, pulverising qualities of fuels, and the determination of volatile matter and ash content. Special attention is paid to the physical characteristics of ash.

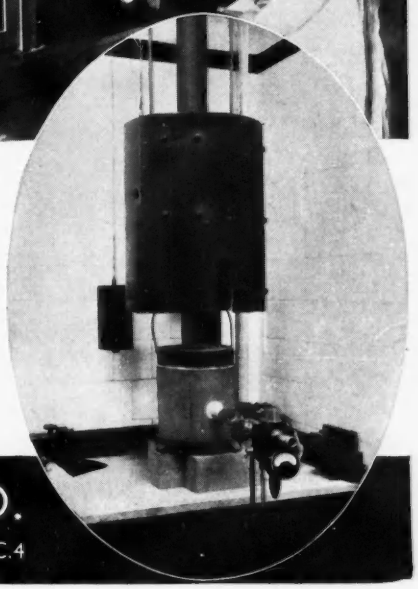


The illustration on the right shows two High Pressure Oxygen Bomb Calorimeters specially arranged for external operation and observation.

The remaining illustrations show the Furnace Room in which is installed apparatus for the determination of carbon and hydrogen content, also automatically controlled electric furnaces, and a close-up view of the Ash Fusion Furnace for temperatures up to 1600°C.

A copy of reprint No. 1179, from a technical paper article: "Reduction of Coal Samples for Analysis" will be sent on application.





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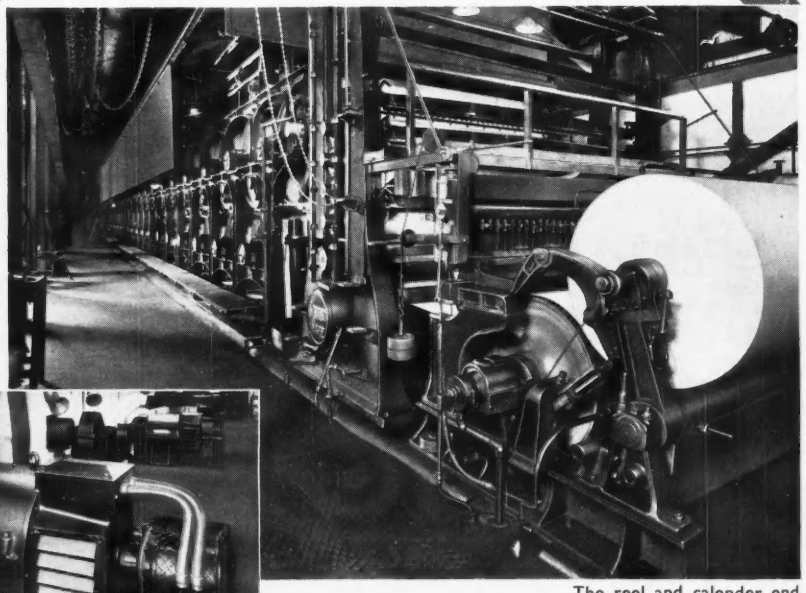
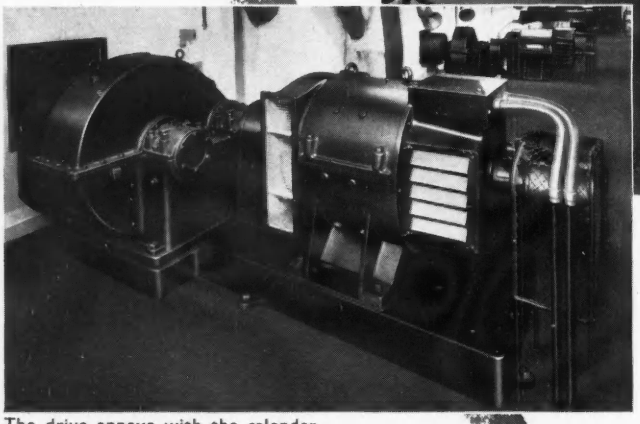
WITTON UNIT SECTIONAL DRIVE for PAPER MACHINES



The reel and calender end of the paper machine.



The drive annexe with the calender motor in foreground.

Following are the principal motor drives of the machine.

- Suction couch, 180 h.p.
- Two suction presses, 70 h.p.
- Three dryer sections, each 110 h.p.
- One calender, 110 h.p.

  The reel is belt driven from the calender.

The above paper machine at the Imperial Paper Mills, Gravesend, has recently been completely modernized with G.E.C. driving and control equipment.

Complete automatic control is provided.

The whole of the equipment was built and tested at Witton Engineering Works.

STEEL
in the making...

1. Charging Open-Hearth Melting furnace.
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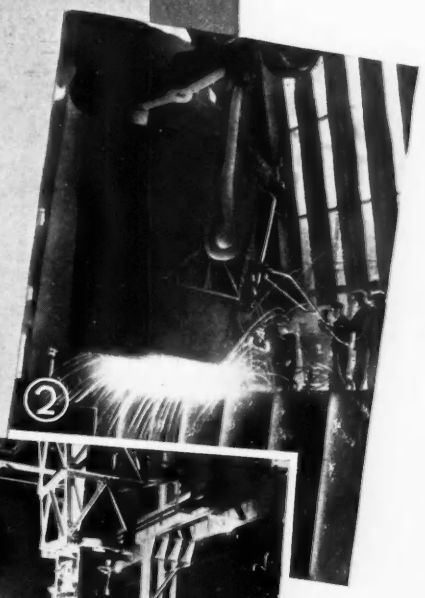
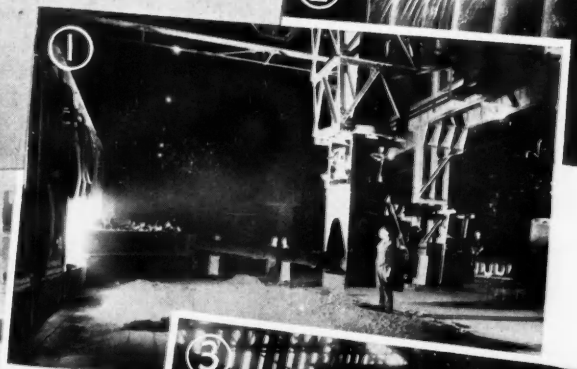
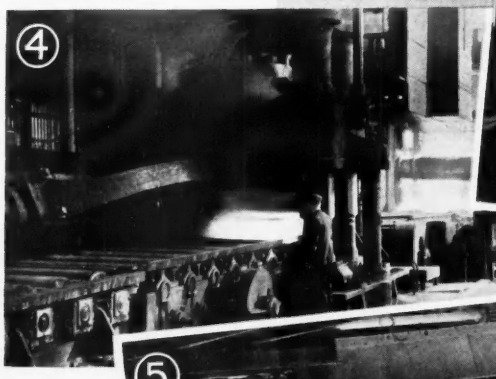
4. Slabbing and Blooming mill with guillotine.
5. Rolling steel plates.







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